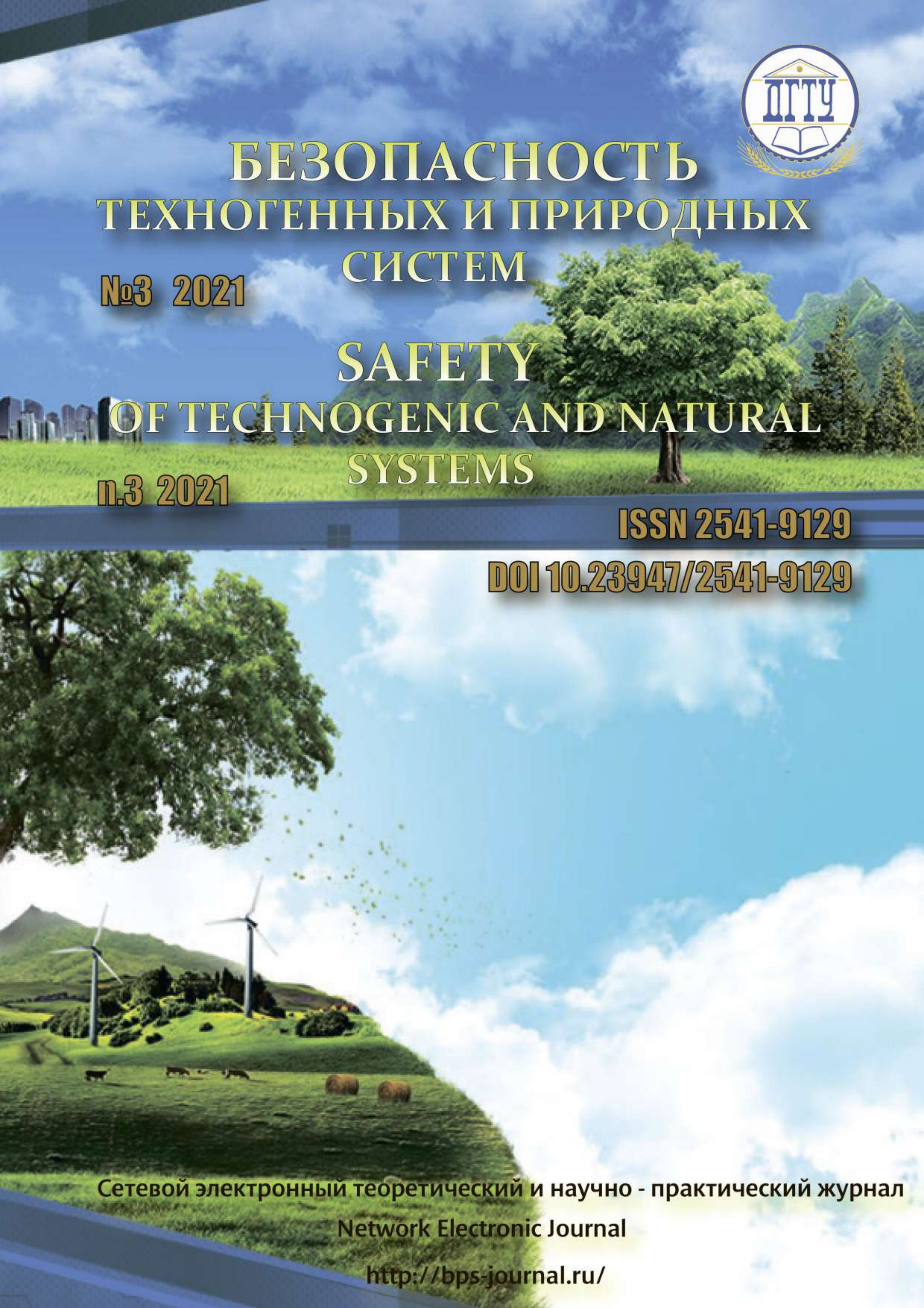

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Energy efficiency analysis of air dehumidification methods that determine safe microclimatic working conditions

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Introduction. The article deals with the issues related to provision of air humidity parameters required for non-hazardous operation of various technical facilities.

Problem Statement. The paper considers analytical methods for energy efficiency assessment of adsorption and condensation methods of air dehumidification, which provide safe microclimatic working conditions, and the influence of the operating modes of dehumidifying plants on the parameters of the microclimate.

Theoretical Part. As indicators of the energy efficiency of each of the methods, it is proposed to use the energy costs that are minimally necessary for the implementation of ideal physical dehumidification processes and per unit mass of water units emitted from air. This ensures safe and comfortable microclimatic working conditions with minimal energy costs. The ratio of the specific energy costs of the condensation and adsorption methods shows their comparative efficiency. An electronic Id-diagram was used to determine the air parameters in the implemented dehumidification processes (cooling, condensation and adsorption of water vapor).

Conclusion. Analytical dependences are obtained for the analyzed energy efficiency indicators that provide safe and comfortable microclimatic working conditions with minimal energy costs. Numerical estimates were carried out according to the most probable modes of dehumidification processes and air parameters. The parametric restrictions on the implementation of the adsorption dehumidification method are justified, in which it becomes energetically more profitable. The conditions under which it is possible to implement a combined dehumidification method to ensure safe microclimatic working conditions are determined.

Keywords: safe microclimatic working conditions, air dehumidification, moisture content, enthalpy, energy efficiency.

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Introduction. One of the main tasks solved when ensuring the safety of operation of various technical facilities is the compliance with the temperature and humidity (microclimatic) parameters of the air environment outside and inside the facility set by the regulatory documentation [1]. First of all, this applies to the parameters of air humidity inside the object. High humidity refers to harmful production factors and, in certain cases, can cause condensation on various surfaces, the occurrence of metal corrosion [2], damage to electronic elements and other undesirable consequences. In this case, the increased humidity becomes a dangerous production factor. For example, fogging the windows of a vehicle increases the risk of a traffic accident. The appearance of condensate inside tanks and pressure vessels and subsequent corrosion can lead to their explosive destruction. Therefore, the humidity parameters that determine safe working conditions are subject to constant monitoring and control during the operation and storage of technical objects, which also provides integral indicators of their quality and reliability at a sufficient level [3]. Most often, there is an excess of the established humidity parameters inside the operated objects as a result of technological processes, condensation from the air, precipitation, loss of tightness of water supply systems, flooding and other natural and man-made impacts on the object. This makes it necessary to dehumidify the air to solve technological problems and ensure safe microclimatic working conditions in almost all sectors of the country's economy, especially in ventilation systems of various underground structures, "clean zones" of microelectronics enterprises, when storing agricultural products [4–7]. Currently, in order to bring the humidity parameters inside the objects to the normalized values, various dehumidifying installations are used.

Energy efficiency of air treatment processes in air conditioning systems is currently provided by a variety of methods and various measures [8–10], but in practice, the choice of energy-efficient solutions, especially for air dehumidification processes, is very difficult due to the influence of numerous factors. The issues of increasing the energy efficiency of dehumidification processes for various methods and schemes are considered in sufficient detail in [11–14]. However, there are no comparative efficiency estimates for different methods under the same conditions for the implementation of these processes. Therefore, the formulation of energy efficiency criteria and obtaining numerical values for various options for the implementation of air dehumidification processes that determine safe microclimatic working conditions is an urgent scientific task. At the same time, it is necessary to take into account that the most effective industrial dehumidifiers are built on adsorption and condensation methods of air dehumidification [15].

Problem Statement. Let us consider the energy efficiency of the adsorption and condensation methods by determining the minimum necessary energy costs for the implementation of ideal thermodynamic processes of dehumidification of a certain volume of air, the mass of the dry part of which is m = 1 kg. In this case, the same final values of the moisture content are set, determined by the safety requirements, and the initial conditions of the air before dehumidification are the same for both methods.

It should be noted that a significant influence on the efficiency of the process of reducing humidity in the room to ensure safe microclimatic working conditions is not the temperature of the air supplied inside, but its moisture content, i.e. the amount of water vapor per a kilogram of dry air, which follows from the thermodynamic analysis of the processes [14–15]. In addition, the real energy costs in dehumidifiers implementing the methods under consideration may be significantly higher due to losses that inevitably occur in actual processes, in contrast to the ideal thermodynamic processes considered in this study.

The main ideal thermodynamic processes in the adsorption method of dehumidification are the processes of water vapor condensation on the cooling surface of the air cooler when its temperature becomes lower than the dew point temperature of the dehumidified air. The dew point temperature t_p at a known barometric pressure (or compressed air pressure) p is uniquely related to the moisture content of the air in the saturation state $d_н$. This follows from the fact that the moisture content $d_н$, in turn, uniquely depends on the partial pressure of saturated water vapor $p_н$ [14]:

$$d_н = 622 \cdot p_н/(p - p_н). \qquad (1)$$

The dependence of the partial pressure of saturated water vapor $p_н$ on the temperature $p_н = f(t)$ is established according to the tables of the thermodynamic state of moist air. Consequently, when the air is cooled, its temperature reaches the value determined from equation (1), water vapor begins to condense in the air and this temperature is called the dew point temperature. Uncontrolled condensation of water vapor, as already noted, is a dangerous production factor, and the dew point temperature must be reduced. Since the pressure of saturated water vapor $p_н$ decreases with a decrease in temperature, therefore, the lower the dew point temperature of the air, the lower its moisture content. Therefore, to obtain drier air with low moisture content, it is necessary to lower the temperature of the cooling surface.

The energy costs for the implementation of the air cooling process are the main ones for the condensation method of dehumidification, but not the only ones. If the temperature of the cooling surface is less than 0°C, the condensate falling out on it freezes. This requires an additional amount of energy. In addition, with a long duration of the dehumidification process, it is necessary to take into account the energy costs of the air cooler thawing process.

Main physical processes in the adsorption method of dehumidification are the processes of adsorption of water vapor from the air when passing it through special substances — adsorbents. The most common adsorbent in modern dehumidifiers is granular silica gel, which is a material with a high specific surface area (up to 800 m^2/g) and a large amount of sorption holes. This leads to a sufficiently high adsorption capacity of silica gel, which reaches up to 30 % by weight [15]. The process of water vapor adsorption when air is passed through the adsorbent is theoretically carried out without heat supply or removal. In this case, the enthalpy of the air remains constant, which does not require energy costs. However, to restore the absorption capacity of silica gel during the operation of air dryers, it is necessary to periodically regenerate its properties by heating to a temperature of 200–250°C or calcinate at a temperature of 700-800°C [14]. These processes require significant energy costs.

Thus, the main physical processes associated with energy costs in the condensation method of air dehumidification are the processes of air cooling with water vapor condensation, as well as the processes of ice freezing and thawing of icy surfaces of air coolers, if it is necessary to dehumidify the air to negative dew point temperatures. In the adsorption method of air dehumidification, such processes are the processes of desorption of water vapor from adsorbents, carried out by heating or calcining the latter.

To analyze the energy costs in the processes under consideration, we will use the Id diagram of moist air [15].

Theoretical Part. The ideal processes of adsorption dehumidification and cooling of air with the formation of condensate, accompanied by a decrease in moisture content, in the Id diagram have the form shown in Fig. 1 (BК, AB and BC processes).

Each of the points denoting the initial and final states of the air in the processes under consideration corresponds to certain values of the parameters [14]: temperature *t*,°C, relative humidity φ,%, moisture content *d*, g/kg d. a. (grams of water vapor per kilogram of dry air), dew point temperature *t*, °C, enthalpy (heat content) *I*, kJ/kg d. a. The initial state of the air (point A in Fig. 1) is set, as a rule, by the temperature t_A and relative humidity φ_A. The remaining parameters are determined using a graphical or electronic Id diagram. The final state of the air after cooling at a constant moisture content before condensation begins (the dew point for the air of state A is point B in Fig. 1), is determined as the intersection point of the line φ = 100 % and the line $d_A = const$.

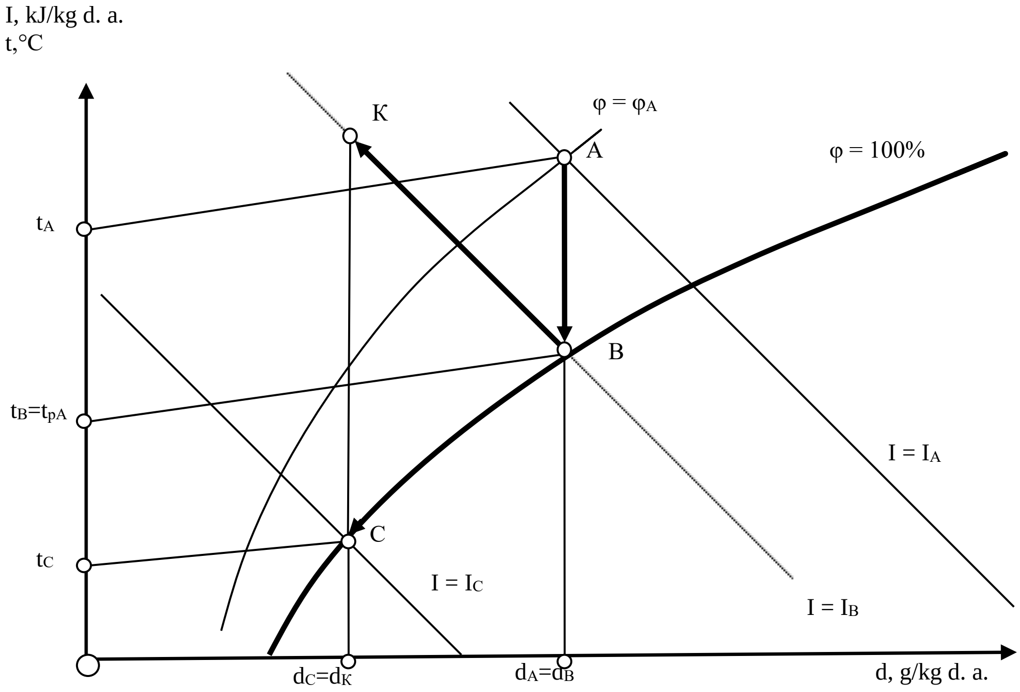

Fig. 1. Processes of condensation and adsorption of water vapor from the air:

AB — air cooling process without vapor condensation;

BC — air cooling process with condensation of water vapor;

BК — water vapor adsorption process at a constant enthalpy

The process of condensation of water vapor during air cooling begins at point B, passes along the line φ = 100 % and ends at point C, the position of which is determined by the specified final drying temperature t_C (dew point temperature). This dew point temperature corresponds to the line of constant moisture content of the air $d_K = d_C = const$ also at the end point K of the adsorption drying process. The dew point temperature in this case is determined from the need to ensure safe microclimatic working conditions by preventing the occurrence of such a dangerous production factor as condensation. Therefore, the dew point temperature of the air after dehumidification should be lower than the possible temperatures of surfaces where condensation is dangerous.

The position of point K is determined by the intersection of the line of constant enthalpy $I_B = const$ and the line $d_C = const$. For example, Table 1 shows the values of air parameters at the considered points, determined using an electronic Id diagram.

Table 1

Air parameters at characteristic points of processes

Parameter		**Dimension**	**A**	**B**	**C**	**К**
Temperature	t	°C	35	26	–15	77
Rel. humidity	φ	%	60	100	100	≈0
Moisture content	d	g/kg d. a.	21.4	21.4	1.0	1.0
Dew point temperature	t_p	°C	26	26	–15	–15
Enthalpy	I	kJ/kg d. a.	90.4	80.8	–12.6	80.8

The amount of heat Q_x, kJ, removed by the refrigeration unit from the air, for the implementation of the processes of cooling and condensation of water vapor with its subsequent crystallization on the cooling surface, is determined by the formula

$$Q_x = m(I_A - I_C) + \lambda m(d_A - d_C)/1000. \tag{2}$$

where m — the mass of the dry part of the cooled air, kg d. a.; λ — the heat of crystallization condensation, kJ/kg, for water λ = 335 kJ/kg.

In formula (2) and in other formulas where the moisture content d is used, we use the conversion factor "1000", with which the dimension of g/kg d. a. is reduced to the dimension kg/kg d. a.

The minimum energy required for the operation of the compressor of the refrigeration unit $L_к$, kJ, is proportional to the number of air from exhaust heat Q_x and depends on the size of the refrigeration ε_x coefficient defined by the thermodynamic cycle refrigeration system:

$$L_к = Q_x/\varepsilon_x. \tag{3}$$

To ensure the continuity of the dehumidification process, it is necessary to thaw the air coolers. Therefore, to the operation of the compressor, determined by formula (3), it is necessary to add the cost of melting the ice formed in the air coolers $Q_{пл}$, kJ:

$$Q_{пл} = \lambda m(d_A - d_C)/1000. \tag{4}$$

The energy consumption for the BК adsorption process (Fig. 1) at a constant enthalpy is zero. However, the implementation of continuity of the necessary regeneration of the adsorbent, the energy cost of which are determined by the heat $Q_д$, kJ, is required for evaporation of water molecules absorbed by the adsorbent:

$$Q_{д} = rm(d_A - d_C)/1000, \tag{5}$$

where r — the specific heat of evaporation, kJ/kg.

According to the reference data at 200°C specific heat of evaporation r =1940 kJ/kg, at a temperature of 300°C — r =1400 kJ/kg.

To carry out the process of desorption of water from an adsorbent with a dry mass m_a, it is necessary to heat it (for silica gel, usually to a temperature of t_a = 300°C). The energy costs for this process $Q_н$ will be:

$$Q_н = [c_a m_a + c_в m(d_A - d_C)/1000]t_a, \tag{6}$$

where c_a — the heat capacity of the adsorbent, kJ/(kg·K); $c_в$ — the heat capacity of water, kJ/(kg·K).

For silica gel, according to reference data, c_a = 0.92 kJ/(kg·K), for water we accept $c_в$ = 4.2 kJ/(kg·K).

The minimum possible mass of the adsorbent m_a, which must be heated for the desorption process, can be estimated by its adsorption capacity. For silica gel, the adsorption capacity significantly depends on several factors: air flow velocity, pressure, granule structure and size, regeneration temperature, etc. The adsorption capacity shows how much vapor can be absorbed by an adsorbent of a single mass or volume. Higher values correspond to low air flow rates, fine fractions and high regeneration temperatures. We assume a sufficiently high value of the adsorption capacity of silica gel γ = 0.05 (or 5 %) by weight [15]. Then the mass of the adsorbent required for the adsorption of water vapor and their subsequent desorption will be determined by the formula

$$m_a = m(d_A - d_C)/(1000 \cdot \gamma). \tag{7}$$

There are no other costs for this drying method. Then the energy efficiency Э of these two methods can be estimated by dividing the total energy costs of the condensation method by the costs required for the adsorption method:

$$Э = (L_к + Q_{пл})/(Q_{д} + Q_н). \tag{8}$$

Substituting expressions from formulas (2-7) into this formula, after the transformations we get:

$$Э = \frac{1}{r + (c_в + c_a/\gamma)t_a}\left[\frac{1000(I_A - I_C)}{(d_A - d_C)\varepsilon_x} + \lambda\left(1 + \frac{1}{\varepsilon_x}\right)\right]. \tag{9}$$

If the Э indicator is greater than one, then the condensation method is worse than the adsorption method in terms of energy costs. If the indicator is less than one, then the condensation method is better. A direct analysis of formula (9) does not allow us to draw an unambiguous conclusion about the energy efficiency of a particular method of air drying, since the value of the proposed indicator Э is determined by a number of parameters, the value of which vary in fairly wide ranges. These include the regeneration temperature of silica gel t_a, its adsorption capacity γ, the cooling coefficient ε_x, the parameters of the air after dehumidification at point C, which are determined from the need to ensure safe microclimatic working conditions. Therefore, we will conduct an analysis of energy efficiency based on the results of calculations, using the approaches of a multifactorial study.

Discussion. Let us perform as an example the calculation of the economic efficiency indicator according to formula (9) using the data given in Table 1.

$$Э = \frac{1}{1400 + (4{,}2 + 0{,}92/0{,}05)\cdot 300}\left[\frac{1000\cdot(90{,}4 + 12{,}6)}{(21{,}4 - 1{,}0)\cdot 2} + 335\cdot\left(1 + \frac{1}{2}\right)\right] = 0{,}37\,.$$

The obtained result shows that the energy costs of the adsorption method in this case are 2.7 times higher than the costs of the condensation method. If the cooling coefficient ε_x in formula (9) decreases to 1, the costs of the condensation method will increase, which will lead to an increase in the indicator *Э*, which will be equal to 0.7. The costs of the adsorption method in this case are also greater than the costs of the condensation method, but only by 40 %. This is due to the large specific energy costs for the regeneration of silica gel (for heating the adsorbent and evaporation of one kilogram of water at normal atmospheric pressure) E_{ya}, kJ/kg. In formula (9), these costs are reflected by the denominator of the first multiplier of the right part. We will analyze the dependence of these specific energy costs on the regeneration temperature t_a and the adsorption capacity γ of silica gel.

$$E_{ya} = r + (c_в + c_a/\gamma)t_a. \qquad (10)$$

For the above data, the specific energy costs will be equal to

$$E_{ya} = 1400 + (4,2 + 0,92/0,05)300 = 8180 \text{ kJ/kg}.$$

A change in the regeneration temperature t_a leads to a nonlinear change in energy costs, since the evaporation heat r changes simultaneously. Graphs of changes in the specific energy costs for regeneration when the regeneration temperature changes from 100 to 400°C at different values of the adsorption capacity of silica gel are shown in Fig. 2.

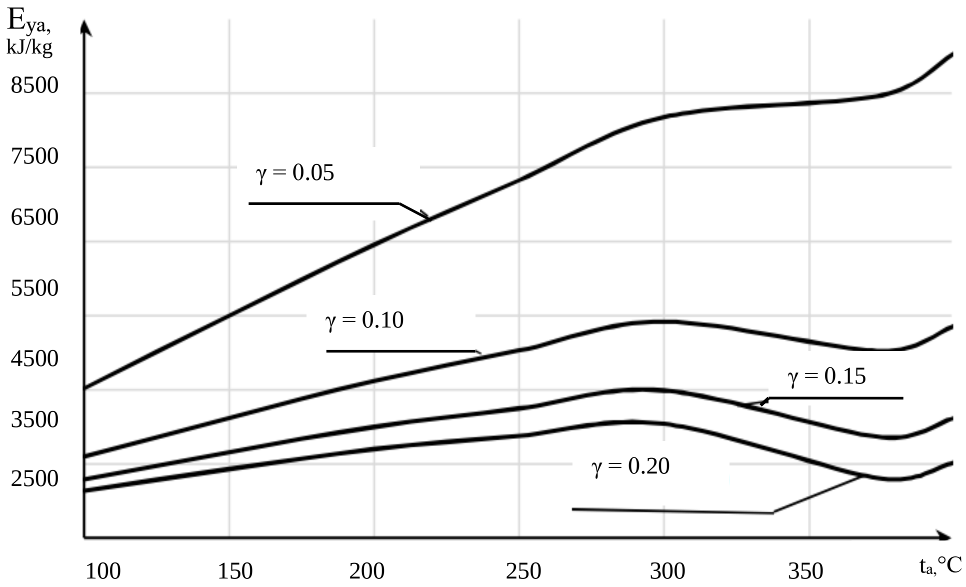

Fig. 2. Dependence of specific energy costs on temperature

As it can be seen from the above graphs, an increase in the silica gel regeneration temperature above 375°C is impractical from the point of view of energy costs. The local minimum of specific energy costs in this area is explained by the fact that at a temperature of 374.15°C, the heat of evaporation becomes equal to 0 due to the water reaching a critical state.

More significant for reducing energy costs is an increase in the adsorption capacity of silica gel γ. The calculations used the value $\gamma = 0.05$, which corresponds to the average value of the flow or dynamic adsorption capacity of silica gel [15]. If the calculations use the values of the static or equilibrium adsorption capacity of silica gel on water, which are determined by the value of the maximum possible amount of moisture absorbed by a unit of mass (or volume) of the adsorbent under static or equilibrium dynamic conditions, then the specific energy costs will be significantly lower. Thus, at $\gamma = 0.1$ and the regeneration temperature $t_a = 300$°C, the value $E_{ya} = 5420$ kJ/kg.

The results of calculations of the specific energy costs E_{ya} at different regeneration temperatures and the adsorption capacity of silica gel are shown in Table 2.

Table 2

Energy costs of the E_{ya} adsorption method, kJ/kg

Regeneration temperature	Vaporization heat	γ = 0.05	γ = 0.10	γ = 0.15	γ = 0.20
t_a, ^{0}C	r, kJ/kg				
100	2256	4520	3600	3290	3140
150	2112	5500	4120	3660	3432
200	1941	6460	4620	4000	3700
250	1675	7330	5030	4250	3880
300	1404	8180	5420	4490	4040
375	0	8475	5025	3860	3300
400	0	9040	5360	4120	3520

Similarly, we will analyze the specific energy costs for the condensation method of drying $E_{ук}$, kJ/kg, the value of which is determined by the expression in square brackets in formula (9):

$$E_{ук} = \frac{1000(I_A - I_C)}{(d_A - d_C)\varepsilon_x} + \lambda(1+\frac{1}{\varepsilon_x}) \cdot \qquad (11)$$

For the air parameters given in Table 1, $E_{ук}$ value will be equal to:

$$E_{ук} = \frac{1000\cdot(90{,}4+12{,}6)}{(21{,}4-1{,}0)\cdot 2} + 335\cdot(1+\frac{1}{2}) = 3030 \text{ kJ/kg.}$$

This value shows the minimum required energy costs for "removing" 1 kg of water vapor from the air. As it can be seen, the obtained value is less than all the values given in Table 2. Therefore, it can be concluded that the condensation method is more efficient in terms of energy costs than the adsorption drying method. However, to confirm this conclusion, it is necessary to analyze how the specific energy costs $E_{ук}$ change when the initial and final states of the air change during the dehumidification process. These states on the Id diagram correspond to points A and C (Fig. 1). The position of point A is set by two parameters (for example, temperature and relative humidity). The position of point C is determined by one parameter (usually the dew point temperature). The position of this point is determined based on the need to ensure safe microclimatic working conditions. Initially, we will analyze the influence of the first two parameters on the value $E_{ук}$, i.e. we will assume the temperature of point C to be equal to – 15°C.

The range of air temperature changes is from 10 to 50°C, relative humidity — from 30 to 90 %. An electronic Id diagram was used to determine the air parameters at point A (moisture content and enthalpy). The results obtained are summarized in Table 3. The desired values of the specific energy costs of the condensation method are also given there, determined by formula (11).

The analysis of the results obtained, given in Tables 2 and 3, shows that under certain conditions, air dehumidification by the adsorption method becomes energetically more profitable than the condensation method. It should be noted here that the data in Table 2 are determined by the modes of regeneration of the adsorbent and, therefore, can be selected or assigned based on the technological and design features of the implementation of this method. For example, increasing the energy efficiency of the adsorption method at low temperatures of adsorbent regeneration is in contradiction with the need to reduce the duration of this process.

Table 3

Energy costs of the condensation method $E_{ук}$, kJ/kg

Air temperature t_A, ^{0}C	Parameters	φ = 30 %	φ = 50 %	φ = 70 %	φ = 90 %
20	d_A, g/kg d. a.	4.3	7.3	10.2	13.2
	I_A, kJ/kg d. a.	31.2	38.6	46.1	53.7
	$E_{ук}$, kJ/kg	7140	4570	3690	3220
30	d_A, g/kg d. a.	7.9	13.3	18.8	24.4
	I_A, kJ/kg d. a.	50.6	64.3	78.4	92.6
	$E_{ук}$, kJ/kg	4580	3630	3060	2750
40	d_A, g/kg d. a.	13.9	23.5	33.4	43.6
	I_A, kJ/kg d. a.	76.2	101.0	126.5	152.8
	$E_{ук}$, kJ/kg	3940	3030	2650	2440
50	d_A, g/kg d. a.	23.6	40.3	58.0	76.6
	I_A, kJ/kg d. a.	111.7	155.1	200.9	249.1
	$E_{ук}$, kJ/kg	3250	2640	2370	2230

High values of the adsorption capacity are achieved only with prolonged contact of the adsorbent with the dehumidified air, which leads to low performance of dehumidifiers through the air. Therefore, taking into account these restrictions, the value E_{ya} = 4600 kJ/kg can be chosen as the maximum (minimum) value of the specific energy costs of the condensation method. In Table 2, this mode is indicated in green.

The data in Table 3 are determined by the initial parameters of the air before the drying process, which, in the case of using outdoor air, are determined by climatic and weather conditions. In the case of using indoor air they are determined by the parameters of the indoor air. As you can see, only one value of specific energy costs, highlighted in yellow, exceeds the value selected for comparison from Table 2. This value corresponds to low relative humidity and temperature. This fact is explained by the fact that in this case a significant part of the energy is spent on cooling the air without condensation of water vapor. In Fig. 1, this process is depicted by the segment AB.

Next, we will consider the influence of the dew point temperature at the beginning and end of the drying process on the energy efficiency of the condensation method. To exclude the influence of energy losses on the implementation of the air cooling process without condensation, we will assume that the air has a relative humidity of φ = 100% before drying. Table 4 shows the calculation results. The analysis of the obtained data shows that an increase in the degree of air drying, characterized by the dew point temperature at the outlet of the dryer, leads to an increase in specific energy costs. Consequently, to ensure more stringent requirements for the safety of microclimatic working conditions, large energy costs are necessary. When dehumidifying air that already has a low dew point temperature (less than 5°C), the use of the condensation drying method becomes energetically less profitable than the adsorption method, if the specific energy costs for the regeneration of silica gel equal to 4600 kJ/kg are used for comparison (Table 2). In Table 4, specific energy costs not exceeding 4600 kJ/kg are highlighted in green.

Table 4

Energy costs E_y, kJ/kg, at different degrees of drying

	Parameters		t_{pA} = 0°C	t_{pA} = 5°C	t_{pA} = 10°C	t_{pA} = 15°C
t_{pC},°C	d_A, g/kg d. a.		3.8	5.4	7.6	10.6
	I_A, kJ/kg d. a.		9.4	18.6	29.3	42.1
–10	d_C, g/kg d. a.	1.6	4030	3750	3450	3180
	I_C, kJ/kg d. a.	–6.1				
–15	d_C, g/kg d. a.	1.0	4430	4050	3680	3350
	I_C, kJ/kg d. a.	–12.6				
–20	d_C, g/kg d. a.	0.6	4880	4380	3920	3540
	I_C, kJ/kg d. a.	–18.6				
–25	d_C, g/kg d. a.	0.4	5460	4790	4220	3760
	I_C, kJ/kg d. a.	–24.3				

Conclusion. The considered results of the study show that the condensation method exceeds the adsorption method of air dehumidification in most calculated cases (sometimes several times) in terms of energy costs, while ensuring safe microclimatic working conditions. However, if deep dehumidification is necessary, there is already enough dry air with a dew point temperature at the entrance to the dehumidifier less than 5°C. In this case, adsorption dehumidifiers become more energetically advantageous. This allows us to conclude that when constructing combined dehumidification methods, it is initially advisable to use a condensation dehumidification method to a dew point temperature of 5°C, and then an adsorption method — to the required dew point temperature, which determines safe microclimatic working conditions indoors.

If it is necessary to obtain not only dry, but also air cooled to low temperatures, which prevents the appearance of dangerous production factors associated with an unacceptable temperature increase (for example, in refrigerating units of freezers, refrigerated trucks, cooling systems of special structures, etc.), the condensation method is energetically the most profitable.

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V. V. Deryushev — statement of the problem, development of the concept of the article. E. E. Kosenko — description of the results and formulation of the conclusions of the research; V. V. Kosenko — critical analysis of the literature; M. A. Krivchuk — tabular representation of the results; I. V. Deryushev — collection of statistical data; A. S. Timofeev — graphical representation of the results.

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Main aspects of vibroacoustic factors assessment

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Introduction. In the age of automation and mechanization of labor, noise and vibration have become the leading dangerous and harmful production factors (DHPF) in various industries and agriculture. In order to reduce the harmful effects of vibroacoustic factors on the human body, first of all, it is necessary to evaluate this factor. The article provides general information on the assessment of working conditions under the influence of vibroacoustic factors.

Problem Statement. The aim of this work is to study the main aspects in the assessment of vibroacoustic factors.

Theoretical Part. As basic information, the paper provides the definitions of noise and vibration, their main characteristics, classification, hygienic regulation, the negative impact of these factors on human health, methods of assessment and measures of protection against them.

Conclusion. The study of the main aspects of the assessment of vibroacoustic factors allows us to analyze the DHPF and further develop measures to reduce the negative impact of these factors on the human body.

Keywords: noise, vibration, dangerous and harmful production factors, hygienic assessment.

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Introduction. Among the huge number of dangerous and harmful production factors that have a negative impact on human health, there are those that a human constantly faces: at work, on production sites, in transport and at home.

Such factors include vibroacoustic, containing vibration, noise, infrasound and ultrasound ones (Fig. 1). Vibroacoustic factors are considered one of the most common harmful and dangerous industrial factors and occupy a leading place among the causes of occupational diseases. They are called the "gray plague" of the XX and XXI centuries. It should be noted that these factors can be safely called relative to each other; they all have an oscillatory nature.

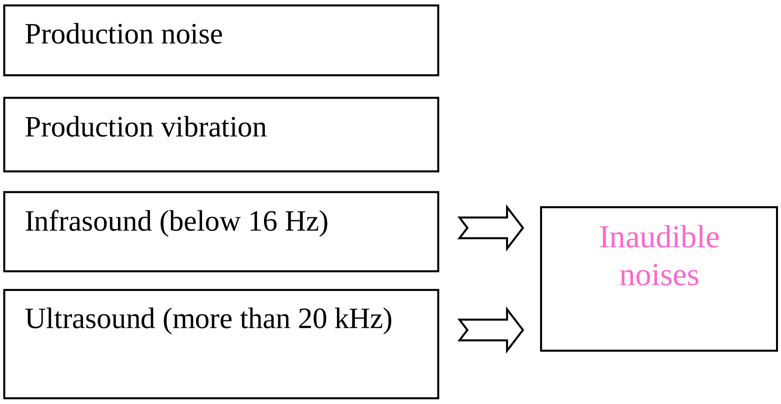


Fig. 1. Vibroacoustic factors

Problem Statement. The task of this work is to study the main aspects of the assessment of workplaces by vibroacoustic factors.

Theoretical Part. *Physical basis of noise level assessment*. From a physical point of view, noise is a chaotic combination of sounds with different intensity and frequency, which has an adverse effect on a person. In turn, sound is called the vibrational motion of particles of an elastic medium, which circulates in the form of waves in solid, liquid and gaseous media. Noise can also be defined as a sensation perceived by the hearing organs during the action of sound waves on them in the frequency range of 16-20,000 Hz.

Hygienic rating and classification of noise. Like any other harmful production factor, noise has a set of indicators by which it is evaluated. The main factors include:

— oscillation frequency (number of vibrations produced per unit time);

— sound intensity (the amount equal to the amount of energy transported by a sound wave through a unit area of the medium per unit time);

— sound pressure — difference between the pressure in the perturbed environment and the mean value of the atmospheric pressure (Fig. 2) [1].

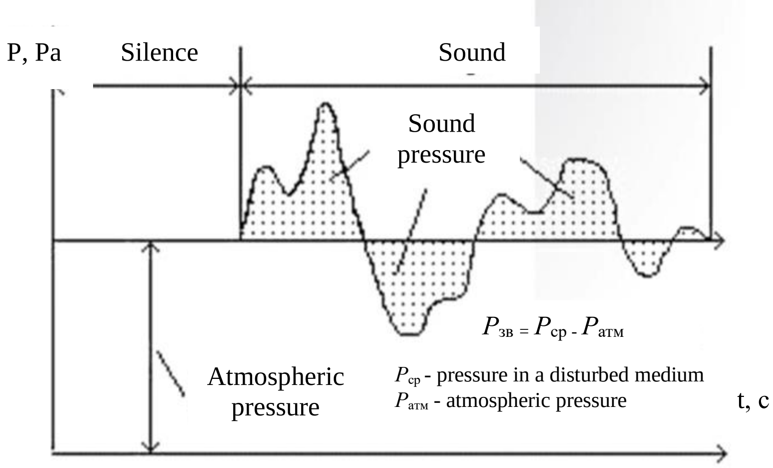

P, Pa
Silence
Sound
Sound pressure
$P_{зв} = P_{ср} - P_{атм}$
Atmospheric pressure
$P_{ср}$ - pressure in a disturbed medium
$P_{атм}$ - atmospheric pressure
t, c

Fig. 2. Sound pressure

The sound intensity *(I, W/m²)* is determined by the formula

$$I = \frac{p^2}{\rho \times c} \tag{1}$$

where p — sound pressure, Pa;

ρ — density of the medium, kg/m^3;

c — sound speed, m/s.

Between the threshold of audibility and the pain threshold is the area of auditory perception, which includes 14 orders of magnitude (Fig. 3). However, with the use of the absolute values of these indicators, it is impossible to draw a conclusion about the working condition in the interval of an 8-hour working shift, so a logarithmic scale is used (the entire area of physical characteristics of sound pressures and intensities is recorded not by multi-digit numbers of absolute values, but by logarithms of the ratios of these values to values equal to the threshold of audibility).

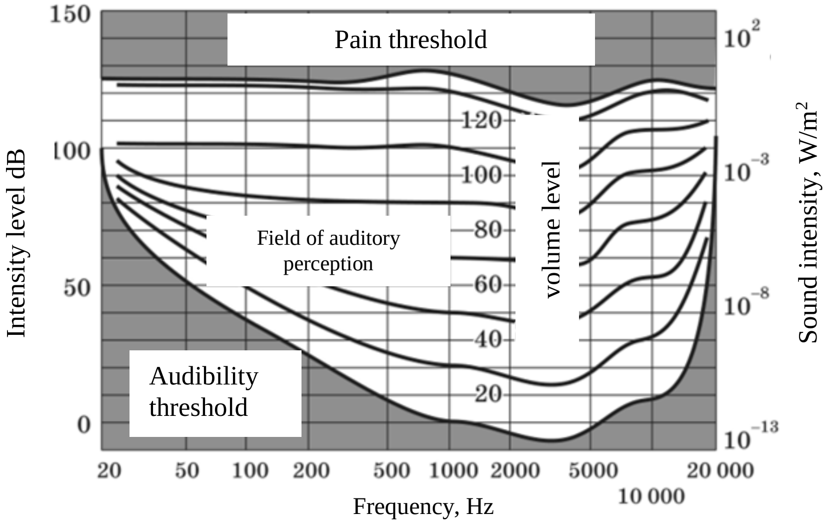


Fig. 3. Audibility diagram for the human ear

In the process of hygienic assessment of working conditions, the entire frequency range is divided into bands of a certain width (spectra).

Octave is a spectrum of frequencies where the ratio of the upper frequency to the lower is two. A third of an octave is a band of a certain frequency width, in which the ratio of the upper frequency to the lower is equal to the cubic root of two [2].

There are a large number of classification features by which noise is distinguished (Table 1).

Table 1

Noise classification

<table>
<tr><th>By the source of occurrence</th><th>By frequency</th><th>By spectrum</th><th colspan="3">By time</th><th>By color</th></tr>
<tr><td>Mechanical</td><td>Low-frequency – up to 300 Hz</td><td>Wide-band</td><td colspan="3">Constan</td><td>White</td></tr>
<tr><td rowspan="2">Aero -, hydro-dynamic</td><td rowspan="2">Midrange-from 300 to 800 Hz</td><td rowspan="4">Tonal</td><td colspan="3">Non-constant</td><td>Gray</td></tr>
<tr><td rowspan="3">Oscillating</td><td rowspan="3">Intermittent</td><td rowspan="3">Pulse</td><td rowspan="2">Pink</td></tr>
<tr><td rowspan="2">Electrodynamic</td><td rowspan="2">High-frequency – more than 800 Hz</td></tr>
<tr><td>Other</td></tr>
</table>

However, the most significant value in working conditions assessment is given to the classification on a temporary basis, in which noise can be divided into constant (the sound level changes by no more than 5 dBA) and non-constant (the sound level changes by more than 5 dBA).

The normalized parameter of constant noise is the sound pressure level; it is measured in 9 octave bands with corresponding geometric mean frequencies. The equivalent (in terms of energy) sound level is a normalized parameter of non-constant noise (Fig. 4) [3].

Constant

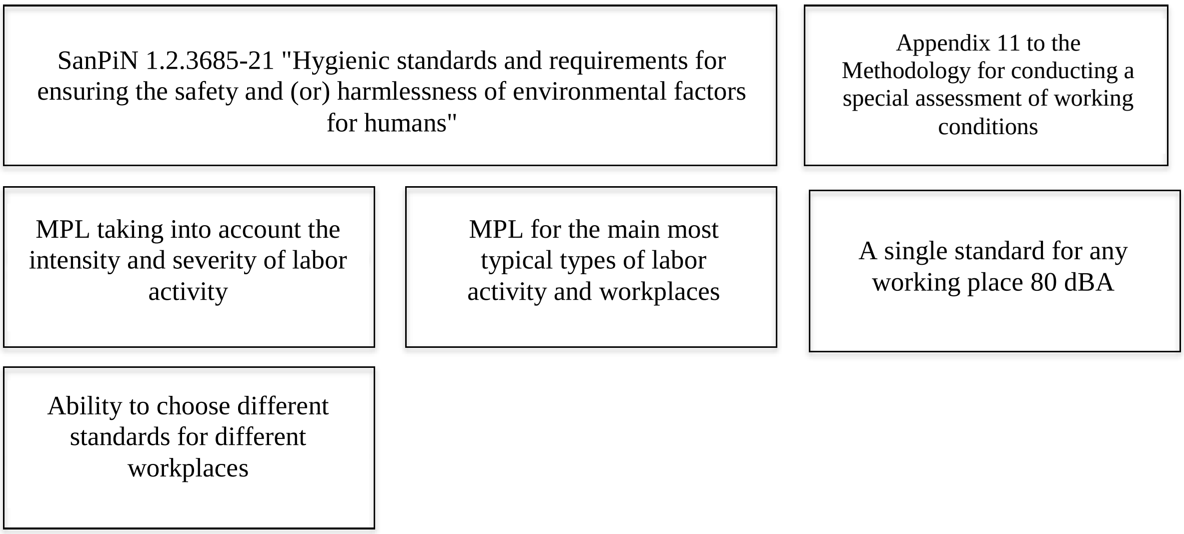
- Sound pressure levels L (dB), in octave frequency bands with average geometric frequencies 31,5; 63; 125; 250; 500; 1000; 2000; 4000 and 8000 Hz

Non-constant

- Equivalent (in terms of energy) sound level, (dBA), in octave frequency bands with average geometric frequencies 31,5; 63; 125; 250; 500; 1000; 2000; 4000 and 8000 Hz

Fig. 4. Noise rating

It can be noted that for two procedures in the field of working conditions assessment, i.e. for production control and special assessment of working conditions (SAWC), the approaches to noise levels rating differ. So, for a special assessment, a single standard was adopted — 80 dBA, and there is a choice for production control (Fig. 5).



SanPiN 1.2.3685-21 "Hygienic standards and requirements for ensuring the safety and (or) harmlessness of environmental factors for humans"

Appendix 11 to the Methodology for conducting a special assessment of working conditions

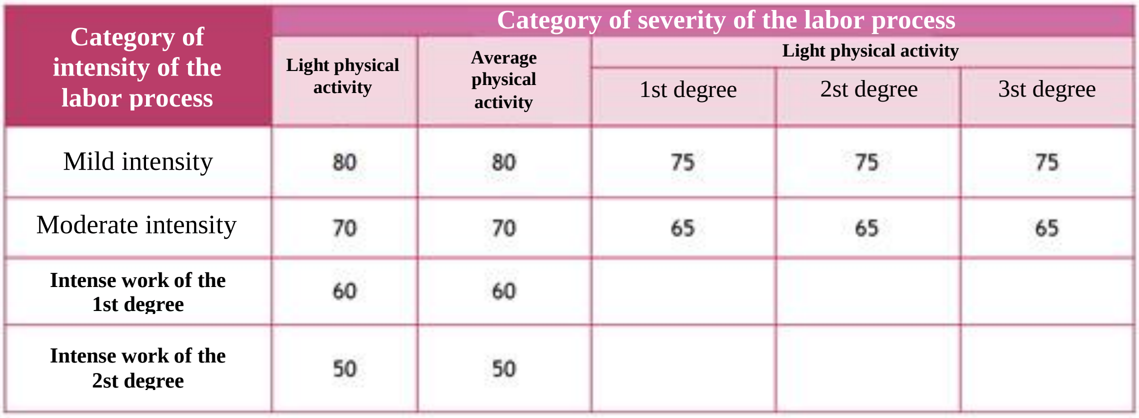
MPL taking into account the intensity and severity of labor activity

MPL for the main most typical types of labor activity and workplaces

A single standard for any working place 80 dBA

Ability to choose different standards for different workplaces

In addition, noise rating depends on the intensity and severity of the labor process (Fig. 6).



Category of intensity of the labor process	Category of severity of the labor process				
	Light physical activity	Average physical activity	Light physical activity		
			1st degree	2st degree	3st degree
Mild intensity	80	80	75	75	75
Moderate intensity	70	70	65	65	65
Intense work of the 1st degree	60	60			
Intense work of the 2st degree	50	50			

Fig. 6. Noise rating depending on the severity and intensity of labor

A possible reason for the differences in the regulation of noise levels within the framework of production control and special assessment of working conditions, according to the authors, is the state policy in the field of assessment of working conditions aimed at reducing jobs with harmful working conditions.

The effect of noise on the body. Noise negatively affects the entire human body, but to a greater extent the organ of hearing and the central nervous system. The effect of noise is characterized by an accumulating effect, which leads to the emergence of an occupational disease — sensorineural hearing loss (Fig. 7) [4].

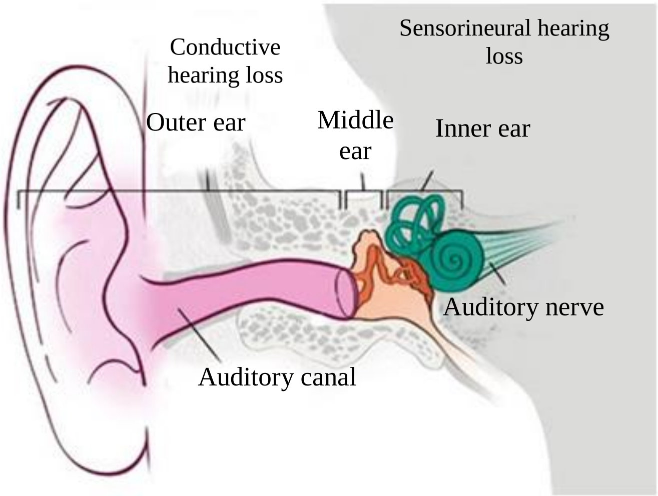


Fig. 7. The effect of noise on the human organ of hearing

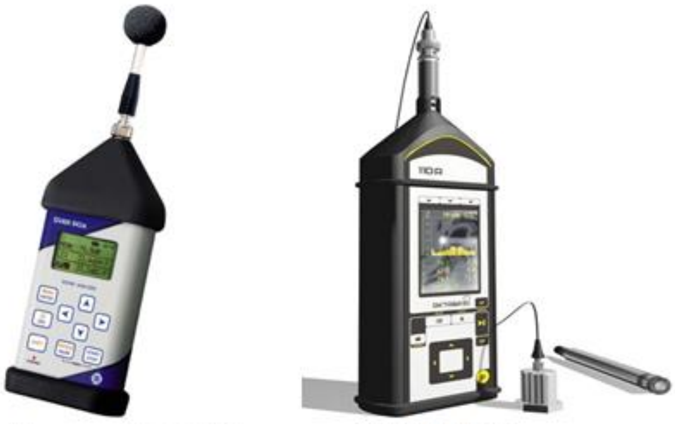
Noise protection. Personal hearing protection equipment includes headphones, anti-noise helmets, earplugs. Collective noise protection measures are divided into two types:

— means that reduce noise at the source of occurrence (changes in the design of equipment, the use of technological processes and equipment that do not emit strong noise);

— means that reduce noise in the propagation path (sound insulation).

With the use of sound absorption, you can reduce noise by only 5-10 dB and with the help of sound insulation — by 30-70 dB.

Measuring instruments. Noise in the workplace is measured using noise meters or noise dosimeters. The most widely used models of noise meters are SVAN and OCTAVE (Fig. 8) [5].



Noise meters SVAN 943A **OCTAVE-110A**

Fig. 8. Noise meters

Physical basis for vibration levels assessment. Vibration is an oscillatory process in mechanical systems, in which a material body after a certain period of time comes to the same stable position. The causes of vibration excitation are unbalanced force effects (reciprocating, rotating, impacts of parts).

Hygienic rating and classification of vibration. Like any other harmful production factor, vibration has a set of indicators by which it is assessed. The main indicators include the amplitude of vibration displacement, the frequency of vibrations, mechanical impedance, vibration velocity and vibration acceleration.

By analogy with noise, a logarithmic scale is used to assess working conditions by vibration (the entire range of vibration speeds and vibration accelerations is recorded not by multi-digit numbers of their absolute values, but by logarithms of the ratios of these values to the corresponding threshold values) [6].

The vibration velocity level *(L_v, dB)* is calculated by the formula

$$L_V = 10lg \times \left(\frac{V^2}{V_0^2}\right) = 20lg \times \left(\frac{V}{V_0}\right), \tag{2}$$

where V – vibration velocity value, m/s;

$V_0=5\cdot10^{-8}$ m/s – speed threshold value.

Vibration acceleration level *(L_a, dB)* is calculated by the formula

$$L_a = 20lg \times \left(\frac{a}{a_0}\right), \tag{3}$$

where a – acceleration value, m/s^2;$a_0=1*10^{-6}$м/с^2 – пороговое значение ускорения.

There are a huge number of classification features by which vibrations are distinguished: by source, by direction of action, by type of source, by time, by method of the influence on a person (Fig. 9).

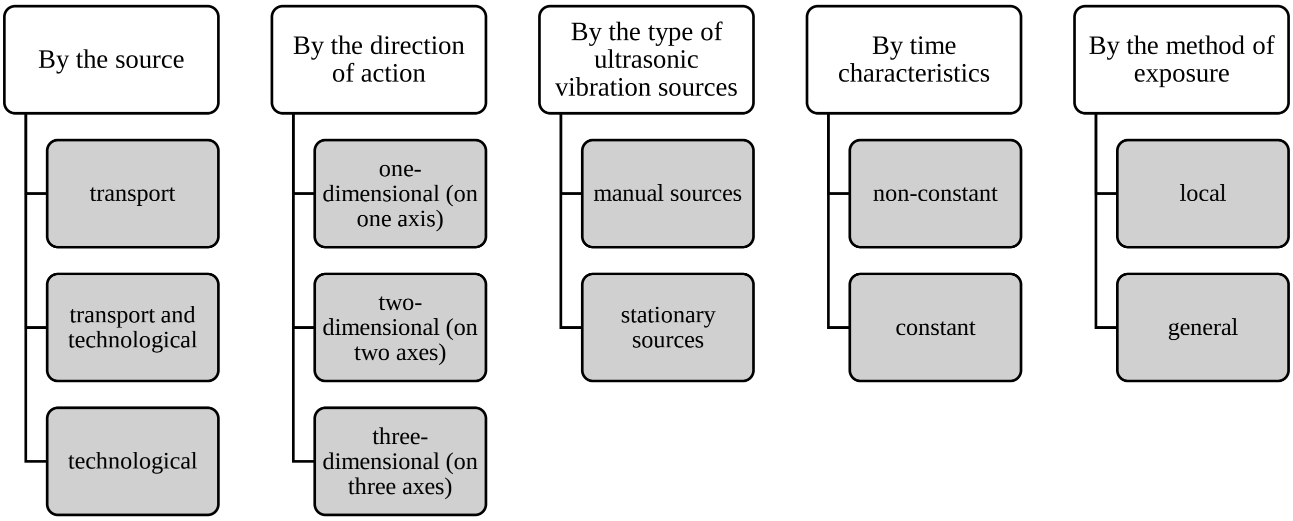

By the source
transport
transport and technological
technological
By the direction of action
one-dimensional (on one axis)
two-dimensional (on two axes)
three-dimensional (on three axes)
By the type of ultrasonic vibration sources
manual sources
stationary sources
By time characteristics
non-constant
constant
By the method of exposure
local
general

Fig. 9. Classification of vibration

But the most important thing for working conditions assessment is a temporary sign, according to which vibration is divided into constant and non-constant. In turn, non-constant vibration is divided into intermittent, oscillating and pulsed [7].

It should also be added that vibration according to the method of exposure to a person is classified as general and local (Fig. 10). Due to the fact that local vibration has a wider frequency range, it is considered more harmful than the general one.

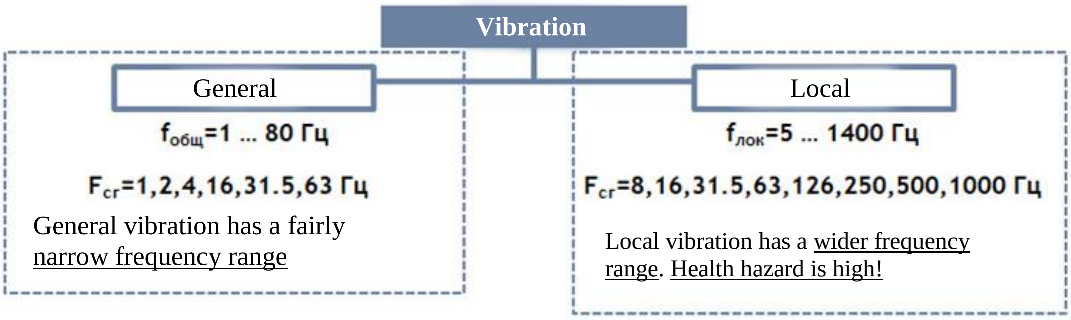

Vibration
General
$f_{общ}$=1 ... 80 Гц
F_{cr}=1,2,4,16,31.5,63 Гц
General vibration has a fairly narrow frequency range
Local
$f_{лок}$=5 ... 1400 Гц
F_{cr}=8,16,31.5,63,126,250,500,1000 Гц
Local vibration has a wider frequency range. Health hazard is high!

Fig. 10. Frequency characteristics of vibration

Depending on the type of vibration (general or local, constant or non-constant), it is rated. The rate parameter of constant vibration is the corrected level of vibration acceleration, and of the non-constant one is the equivalent corrected level of vibration acceleration.

It should be noted that for two procedures in the field of working conditions assessment, that is, for production control and special assessment of working conditions, the approaches to vibration rating differ. Thus, uniform standards have been adopted for a special assessment, and there is a choice for production control depending on the source of vibration (Table 2).

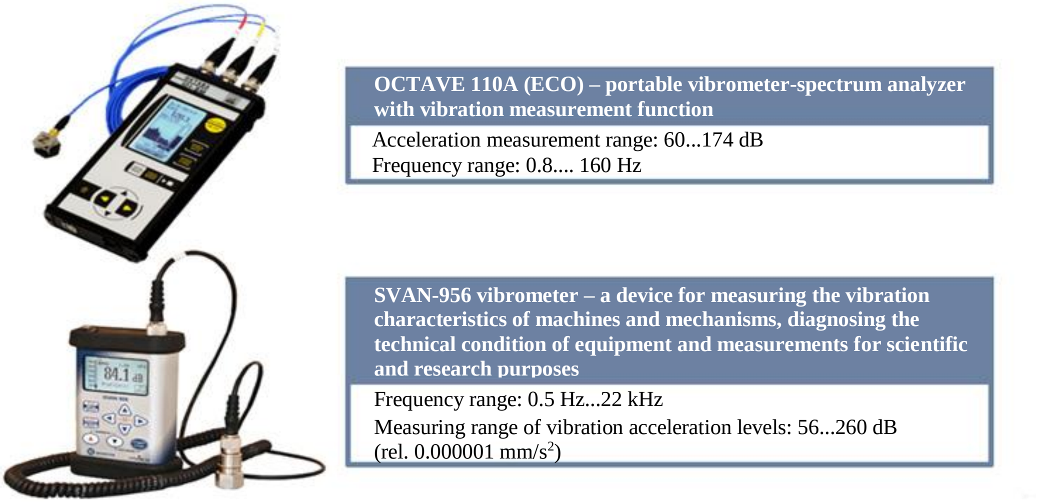
Table 2

Vibration regulation in production control and special assessment of working conditions

Production control Manual 2.2.2006-05	Special assessment of working conditions
Local vibration Use of weighting coefficients for frequency bands, use of AEL for frequency bands	Local vibration Use of AEL for frequency bands
General vibration Use of weighting factors for frequency bands Use of AEL for several categories (according to the source)	General vibration No divisiion by the source Use of AEL for setting the TUA on the Z axis and on the X, Y axes in dB

According to the authors, a possible reason for the differences in the regulation of vibration in the framework of production control and special assessment of working conditions is the state policy in the field of working conditions assessment aimed at reducing jobs with harmful working conditions.

Vibration measurements at the workplace are performed using vibrometers. The most widely used models of vibrometers are SVAN and OCTAVE (Fig. 11) [8].



OCTAVE 110A (ECO) – portable vibrometer-spectrum analyzer with vibration measurement function

Acceleration measurement range: 60...174 dB
Frequency range: 0.8.... 160 Hz

SVAN-956 vibrometer – a device for measuring the vibration characteristics of machines and mechanisms, diagnosing the technical condition of equipment and measurements for scientific and research purposes

Frequency range: 0.5 Hz...22 kHz
Measuring range of vibration acceleration levels: 56...260 dB (rel. 0.000001 mm/s^2)

Fig. 11. Measurement of vibration parameters

The effect of vibration on the body. The impact of vibration on a person is much more complex than that of noise, but it also has a greater negative impact on the nervous system.

An occupational disease caused by exposure to vibration is called vibration disease or "white fingers disease". There are three stages of vibration disease.

At the first stage, there is a violation of skin sensitivity; there is pain and weakness in the hands. The second stage is accompanied by the processes of bringing the fingers together, changing the color of the skin. During the third stage, irreversible changes occur in the cardiovascular and central nervous system, atrophy of the limbs occurs (Fig. 12) [9].

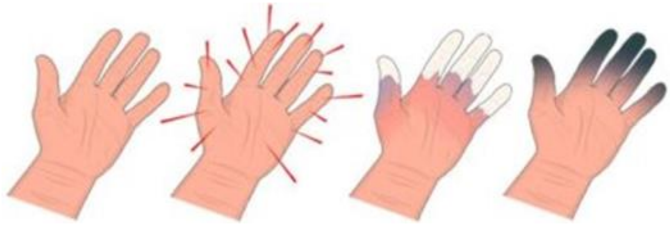


Fig. 12. Vibration disease

The most common diseases are caused by local vibration; it can cause a slowdown in blood circulation in the hands, fingers, forearms, heart vessels. Vibration, which transmits vibrations from the legs to the head, is particularly adversely affected.

Means of protection against vibration. The means of protection against vibration include reducing vibration in its source, reducing vibration on the path of propagation, organizational, technical and therapeutic and preventive measures, use of personal protective equipment (vibration-insulating shoes, soles, special insoles, gaskets, liners, specialized mittens and gloves).

Vibration measurement tools. Vibration can be measured using vibrometers and vibration analyzers.

Vibrometer is a device for measuring vibration velocity. Modern vibrometers, in addition to measuring vibration, determine additional parameters. For example, the Fluke 805 vibrometer also measures the temperature of bearings (Fig. 13).

Fig. 13. Fluke Vibrometer

A vibration analyzer is a more complex measuring device compared to a vibrometer (Fig. 14). Unlike a vibrometer, a vibration analyzer allows you to track vibration in dynamics, that is, with the help of a vibrometer, you can measure vibration at a specific time, and with the help of an analyzer, you can estimate the change in this parameter [10].

Fig. 14. Vibration analyzer

There are many professions that are characterized by exceeding the hygienic standards for vibroacoustic factors. An example of such a profession is the driver of a compressor unit, the noise level of which can reach 100 decibels at a rate of eighty. Accordingly, the class of working conditions at such a workplace will be 3.1 and higher, which determines the need to develop measures to improve working conditions.

Conclusion. The authors of the article conducted a study of the main aspects of the assessment of vibroacoustic factors. This assessment allows you to analyze dangerous and harmful production factors and further develop measures to reduce their negative impact on the human body.

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N. H. Abdrakhmanov — structure of the article, critical analysis, editing; A. V. Fedosov — scientific supervision, formulation of the main objectives of the study, the method of its carrying out, processing of observational data, text editing; A. N. Khamitova — problem statement, formulation of basic concepts of the study, formulation of the conclusions; I. I. Badrtdinova — completion of the text, collection and analysis of the literature data; G. L. Matuzov — development of the concept of the study, data processing observations.

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Improvement of the integrated safety of the labor process of employees

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Introduction. The article proposes a model for assessing the integrated safety of the labor process of workers with the risk of the spread of infectious respiratory diseases, for the development of which multifactorial dependences of occupational risk on working conditions at the workplace were used, taking into account the likelihood of contracting coronavirus infection.

Problem Statement. The objective of this study is to formulate methodological aspects of ensuring the safety of the workplace and the working environment, reflecting the need for constant epidemiological monitoring of objects of control (employees and the ways of virus transmission) with an assessment of the controlled parameters.

Theoretical Part. Official data provided by the Federal State Statistics Service was used as basic information.

Conclusion. The results of the analysis indicate the need for a rapid assessment of occupational risk, taking into account the epidemiological circumstances.

Keywords: labor protection, risk of infection, coronavirus infection, occupational risk, protective equipment.

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Introduction. With the growth of the total population and global urbanization, there is an increase in the level of risk and the rate of spread of infectious diseases, which is due to the high population density and the frequency of human contact. These processes naturally lead to the emergence of new viruses, mutations of the existing ones. So, at the beginning of 2020, the SARS-CoV-2 virus (the causative agent of the COVID-19 disease) received a worldwide epidemic spread and turned into a pandemic. At the time of the spread of the infection, there were no vaccines, specific medications, and there was no single clinical methodology for the therapeutic treatment and prevention of coronavirus [1, 2]. Faced with the severe consequences of contracting coronavirus infection in the form of complications and deaths, the governments of most countries have introduced restrictive measures that have caused serious changes in people's lives. Human security in the conditions of the spread of infectious diseases can be represented in the form of a pyramidal division into several interrelated levels: a safe household environment, a safe working environment and the safety of the population as a whole (Fig. 1).

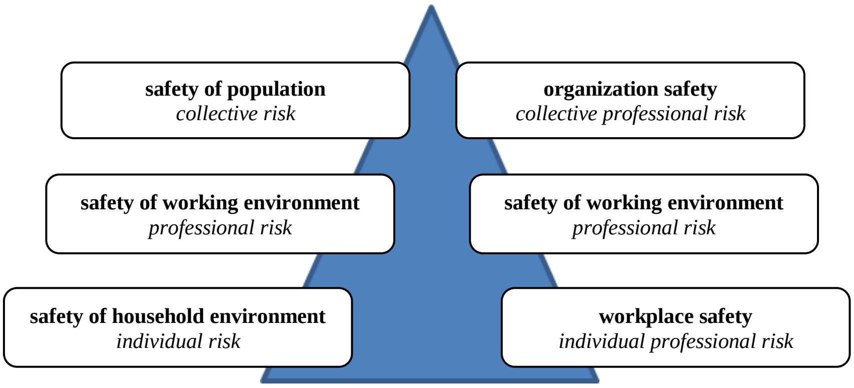
safety of population
collective risk
organization safety
collective professional risk
safety of working environment
professional risk
safety of working environment
professional risk
safety of household environment
individual risk
workplace safety
individual professional risk

Fig. 1. Pyramidal division of the level of human safety in the conditions of the spread of infectious diseases

The central place is occupied by the area of ensuring a safe labor process, for the maintenance of which the resources of health care, sanitary and epidemiological well-being, protection in emergency situations are used. Workplaces are an environment that can accelerate the spread of COVID-19. The control of the level of exposure to SARS-CoV-2 infection in the workplace is carried out through labor protection services in order to reduce the viral load at the enterprise as a whole [3, 4].

Predicting the expansion of coronavirus infection allows us to predict that the end of the pandemic will occur within a few years, so the restrictions and requirements imposed are fixed at the legislative level. The Russian Federation has already adopted regulatory documents regulating the requirements for the prevention of coronavirus: SP 3.1.3597-20 "Prevention of a new coronavirus infection (COVID-19)", SP 3.1/2.4.3598-20 "Sanitary and epidemiological requirements for the design, maintenance and organization of the work of educational organizations and other social infrastructure facilities for children and youth in the conditions of the spread of a new coronavirus infection (COVID-19)", etc.

In addition, the Ministry of Health of the Russian Federation, Rospotrebnadzor constantly update recommendations for employees and employers in a negative epidemiological situation. The employer has the right to independently determine the structure and scope of the system of anti-epidemic measures, taking into account the specifics of the organization, the parameters of the labor process and other characteristics of the enterprise, based on the recommendations of authorized bodies and current legal requirements [5, 6]. In the context of a pandemic, the role of occupational safety specialists in ensuring safe working conditions is increasing through timely identification of infectious and non-infectious hazards, as well as risk assessment and management. The adoption of urgent organizational and administrative measures to monitor, control, prevent, counteract and contain the spread of infection will minimize infection and restore the normal operation of the enterprise [7].

Problem Statement. The objective of this study is to form methodological aspects of ensuring the safety of the workplace and the working environment, reflecting the need for constant epidemiological monitoring of control objects (workers and ways of virus transmission) with an assessment of the controlled parameters. The aim of the work is to modernize the occupational health and safety management system of enterprises, taking into account the analysis of the main changes in the legislative sphere aimed at limiting the coronavirus infection spread and ensuring the population safety. The relevance of the studied issues is also evidenced by the statistical data of state supervisory agencies on the detected violations in the field of anti-epidemic protection at the workplace.

Theoretical Part. The analysis of the circumstances of infection of workers with SARS-CoV-2 allows us to identify the following main ways of infection through contact with infected people or with infected surfaces and objects: during the performance of duties at the workplace, during business trips and official trips, while traveling to the place of work or from work on a vehicle. It should be taken into account that a person infected while performing work functions can infect people around him both at the enterprise and outside it [8, 9].

Methodological aspects of ensuring the safety of the workplace and the working environment, reflecting the need for constant epidemiological monitoring of control objects (workers and ways of transmitting the virus) with an assessment of the controlled parameters, are presented in Tables 1, 2.

Table 1

Organization of a safe workplace (reduction of individual occupational risk)

Object of control	Control methods	Controlled parameters
An employee (an organism susceptible to infection)	Protection of receptors (respiratory hygiene, gloves, special clothing), personal hygiene	Efficiency, frequency of replacement, degree of comfort, processing, disposal
	Distancing of physical interaction	Location and number of workplaces
	Thermometric control of employees	Accuracy and frequency of measurement
	Monitoring the well-being of employees (detection of signs of an infectious disease, testing for infection) and compliance with the self-isolation regime	Efficiency and frequency
Working area (path of transmission of pathogenic agents)	Disinfection of the workplace	Effectiveness of disinfectants, frequency of treatment
	Installation of protective barriers	Location and height, efficiency

Table 2

Organization of a safe working environment (reduction of collective occupational risk)

Object of control	Control methods	Controlled parameters, calculation of the risk of disease	Necessity to calculate the risk of the disease
An employee (an organism susceptible to infection)	Training to prevent the risk of infection	Knowledge assessment	+
	Informing employees about the current situation in the organization, in the region or the country as a whole, about ways to protect against infection	Knowledge assessment	–
	Improving the health of employees	Efficiency, reducing the risk of disease	+
	Social protection of employees	The amount of payments, social discrimination, stigmatization	–
	Changing the production culture	Behavior at work	–
Working area (path of transmission of pathogenic agents)	Time management	Flexibility of the working schedule, transfer to remote work	+
	Optimization of microclimatic parameters and disinfection of the air environment (ventilation, air conditioning, heating, bactericidal protection)	Efficiency, frequency, registration in the journal	+
	Cleaning and disinfection of public surfaces	Efficiency, frequency, registration in the journal	+

The epidemiological situation in the workplace not only affects the health and safety of employees, but also affects the level of stability of their employment.

An important element in the occupational health and safety management system, the presence of which is checked by state inspectors for employers, is the management of occupational risks. The need to make changes to the procedure for assessing occupational risks is caused by the coronavirus pandemic and requires an assessment of the probability of infection of employees. Employers are faced with the problem of effective assessment and management of occupational risks in the workplace [10, 11].

To prepare workplaces for an increase in the risk of infection of employees, it is necessary to conduct an early and further operational assessment of the occupational risk of infection, taking into account the following indicato

$$R = (a_1 \cdot \text{ИОУТ} + a_2 \cdot К_{T1} + a_3 \cdot К_{T2} + a_4 \cdot К_{T3}) \times L \times D \times 3 \times R_t, \qquad (1)$$

where a — the coefficient that takes into account the significance of the parameter;

ИОУТ — integrated assessment of working conditions at the workplace;

$К_T$ — the indicator of individual susceptibility and severity of the consequences of infection ($К_{\text{T1}}$ — takes into account the state of health (the presence of diseases), $К_{\text{T2}}$ — takes into account age, $К_{\text{T3}}$ — takes into account work experience);

L — the indicator of the probability of contact with potentially infected people;

D — the indicator of the probability of an employee's contact with a source of infection (potentially infected people or infected surfaces/materials when performing work functions;

3 — the indicator that takes into account the number of infected employees in the organization;

R_t — the coronavirus spread coefficient is an indicator that determines the average number of people infected by one patient before his isolation according to the methodological recommendations of Rospotrebnadzor of 8.05.2020:

$$R_t = (X_8 + X_7 + X_6 + X_5) / (X_1 + X_2 + X_3 + X_4), \qquad (2)$$

where R_t — the coronavirus spread coefficient, official data on its magnitude (by region and in the Russian Federation as a whole) are published on the Rospotrebnadzor website (Fig. 2);;

$X_1 \ldots X_8$ — the number of registered infected by COVID-19 people in the region for the corresponding day.

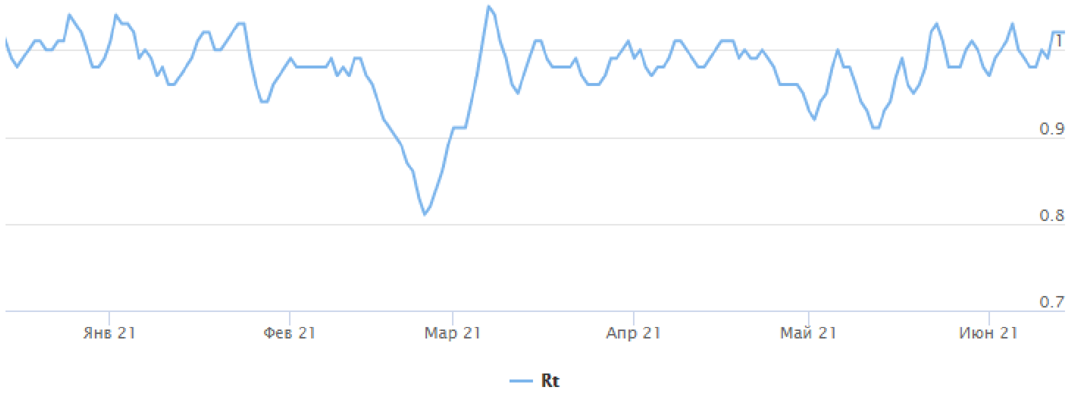

Fig. 2. Data on the spread rate of coronavirus in the Belgorod region

The level of professional risk in the organization is determined taking into account the individual professional risk:

$$У = R/N, \qquad (3)$$

where N — the number of employees in the organization, people.

To determine the epidemiological situation in the Belgorod region, the values of the risk of infection with coronavirus infection and the risk of mortality of the population (the number of 1,541,259 people) were determined (Table 3). The results obtained indicate that the level of acceptable risk is exceeded (10-6), which necessitates the introduction of measures aimed at contain the spread of the coronavirus infection.

Table 3

Indicators of the epidemiological situation in the Belgorod region as of June 2021

Month	Number of infections	Risk of infection	Infection frequency coefficient	Number of deaths	Risk of mortality
June	44997	0.0292	$1.44192 \cdot 10^{-8}$	55	0.001222
May	57481	0.0373	$1.12876 \cdot 10^{-8}$	59	0.001026
April	44803	0.0291	$1.44816 \cdot 10^{-8}$	68	0.001518
March	59618	0.0387	$1.0883 \cdot 10^{-8}$	78	0.001308
February	65845	0.0427	$9.85375 \cdot 10^{-9}$	112	0.001701
January	65903	0.0428	$9.84508 \cdot 10^{-9}$	113	0.001715

When assessing professional risk, it is necessary to take into account the differentiation of the level of risk within one organization [12]. Adjustment of the risk level should be made taking into account changes in the epidemiological picture of morbidity in the country, region, at the enterprise as a whole and in specific structural divisions. Risk ranking can be carried out in two directions — the probability and severity of the impact.

In order to take effective measures to contain the spread of the COVID-19 virus (the causative agent of SARS-CoV-2), it is also necessary to take into account the categorization of workplaces by the level of exposure to infection (very high, high, medium and low), developed by the US Occupational Safety and Health Administration (OSHA) [13, 14]. According to the official data of the Federal State Statistics Service, the employed population of the Russian Federation aged 15-72 years in 2020 was: total — 70,601 thousand people (100%), men — 36,208 thousand people (51.3%), women — 34,393 thousand people (48.7%) [15]. Taking into account the information received, the authors conducted a categorization in accordance with the All-Russian Classifier of Occupations OK 010-2014 (division into groups of professions at the main job) according to the level of risk of infection with coronavirus infection (Table 4).

Table 4

Employed population aged 15-72 years in 2020

Groups of professions at the main job in 2020 (in accordance with All-Russian Classifier of Occupations OK 010-2014)	Total	Percentage ratio		Risk category
		men	women	
Total	100	51.3	48.7	
Managers	5.81	3.15	2.66	1
Specialists of the highest qualification level:	26.34	9.80	16.54	2
– scientific and technical activities	4.58	3.12	1.46	1
– activities in the field of healthcare	2.24	0.74	1.50	4
– activities in the field of education	6.05	0.98	5.07	3
– business and administration	7.59	2.26	5.33	1
– information and communication technologies	1.55	1.27	0.28	1
– law, humanities and culture	4.32	1.42	2.90	1
Specialists of the average qualification level:	13.74	5.63	8.11	
– specialists-technicians (scientific and technical activities)	4.38	3.82	0.56	1
– secondary medical personnel in the field of healthcare	3.55	0.29	3.26	3
– MSS in the field of economic and administrative activities	4.48	1.07	3.40	1
– MSS in the field of legal, social work, culture, education, sports and related activities	1.14	0.28	0.86	1
– technology in the field of ICT	0.21	0.18	0.03	1

Groups of professions at the main job in 2020 (in accordance with All-Russian Classifier of Occupations OK 010-2014)	Total	Percentage ratio		Risk category
		men	women	
Employees engaged in the preparation and execution of documentation, accounting and maintenance:	2.76	0.49	2.26	1
– general profile and maintenance of office equipment	0.75	0.09	0.67	1
– public service	0.79	0.14	0.65	1
– processing of numerical information and accounting of material values	0.73	0.20	0.53	1
– other office employees	0.48	0.07	0.41	1
Employees of the service and trade sector, protection of citizens and property:	15.19	4.61	10.59	2
– individual services	3.59	0.52	3.07	2
–trade (sellers, consultants)	7.31	1.21	6.10	3
– individual care	1.18	0.06	1.11	2
– protection of citizens and property	3.11	2.81	0.30	2
Qualified workers of agriculture and forestry, fish farming and fishing	2.49	1.29	1.20	1
Skilled workers of industry, construction, transport and workers of related occupations:	13.07	10.76	2.31	2
– construction and workers of related occupations (except electricians)	3.08	2.81	0.27	1
– metalworking and machine-building production, mechanics and repair	5.42	5.19	0.23	1
– manufacture of precision tools and devices, workers of artistic crafts and printing production	0.36	0.19	0.16	1
– electrical engineering and electronics	1.54	1.35	0.19	2
– food, woodworking, textile and clothing industries and workers of related occupations	2.68	1.23	1.46	2
Operators of industrial installations and machines, assemblers and drivers:	13.03	11.52	1.51	1
– maintenance of industrial installations and stationary equipment	3.19	2.01	1.18	1
– assemblers	0.26	0.18	0.08	1
– drivers and operators of mobile equipment	9.58	9.33	0.25	1
Unskilled workers:	7.57	4.03	3.54	1
– servants and cleaners	1.64	0.07	1.57	1
– agriculture and forestry, fish farming and fishing	0.55	0.39	0.16	1
– mining, construction, manufacturing and transportation	2.01	1.31	0.70	1
– food preparation assistants	0.19	0.02	0.17	1
– street vendors and other types of street services	0.01	0.002	0.01	1
– garbage collection and other unskilled workers	3.17	2.24	0.93	1

As part of the digitalization of labor protection, a promising direction is the development of software for system analysis and assessment of occupational risks, taking into account the probability of infection with COVID-19 [16]. The modern domestic market in this area is represented by the following development companies: RiskProf service (information and analytical portal "Labor Protection"), the program "Professional Risk Assessment System" (ARM SERVICE group of companies, Samara), the software product "Professional Risk Management System" (Inform Center LLC, Perm Krai), the HSE RMS cloud service for working with professional risks (HSE Lab, Moscow), the Professional Risk Assessment program (Institute of Occupational Safety, Moscow), the Professional Risk Management System program (System Soft LLC, Moscow), the SoftExpert company (SoftExpert ERM software "Enterprise Risk Management"). The largest foreign companies that develop software for assessing professional risks are Vigilant Software (vsRisk), PTA Technologies (PTA), Archer (RSA Archer), Modulo (Modulo Risk Manager), RM Studio, Digital Security.

The main elements of the assessment of the risk of infection of employees with COVID-19 (relative to the structure of the general assessment of occupational risks) are:

1. Objects of assessment (workplace, work activity, emergency situation).

2. Characteristics of hazards (according to paragraph 35 of Order of the Ministry of Labor of 19.08.2016 No. 438n "On approval of the Standard Regulation on the Occupational Health and Safety Management System").

3. Assessment of the probability of occurrence and severity of consequences (potential triggers are taken into account, the correlation of risks by the source of danger).

4. Risk ranking.

5. Development of measures to reduce the level of risk + personal response strategies (with an indication of deadlines and responsible persons).

The regulatory and legal regulation of labor protection for the period of an unfavorable epidemiological situation is at the stage of active development, some draft laws have already been adopted. The prospects for further developments on the issue under consideration are the introduction of an effective occupational health and safety management system in organizations, taking into account the effectiveness of their practical application.

The authors propose the following scheme for improving the occupational health and safety management system, taking into account the risk-oriented approach:

1. Development of an effective risk management structure: development of the organization's anti-epidemic policy and local documents (orders, regulations, programs, instructions), appointment of responsible persons for the implementation of preventive measures based on the management structure, the amount of resources and the official powers of employees.

2. Digitalization and introduction of end-to-end technologies in labor protection:

2.1. Automation of control systems for the issuance and operation of personal protective equipment (vending machines for PPE, monitoring scanning of violations during the operation of PPE by employees).

2.2. Introduction of augmented and virtual reality technologies in occupational safety training.

2.3. Introduction of machine learning and artificial intelligence technologies.

3. Development of a flexible labor organization system (optimization of the labor process schedule):

3.1. Introduction of remote work mode for employees who are at high risk.

3.2. Implementation of a time management system, taking into account the effective distribution of work shifts to achieve minimal employee contact.

3.3. Development of an emergency program for switching to remote operation.

4. Optimization of social protection of employees (development of a system of remuneration during the spread of infections, protection from social discrimination and stigmatization).

5. Development of employee wellness programs:

5.1. Organization of detoxification nutrition.

5.2. Implementation of projects for the development of healthy lifestyle, physical culture and sports for employees.

5.3. Protection of psychological health (trainings).

6. Improvement of the system of medical supervision of employees in order to identify physical or psychological pathology affecting the performance of professional duties: thermometric control, testing for the presence of infection and organization of vaccination at the enterprise.

7. Organization of collective antiviral protection of the air environment (antibacterial ventilation/air conditioning and air disinfection).

8. Correlation of occupational risk assessment taking into account the risk of infection of employees (introduction of an electronic system for recording cases with risk calculation).

9. Inclusion of the emergency preparedness procedure in the emergency management system. Development of a personal response strategy.

Conclusion:

1. The employer's obligation to ensure and maintain safe working conditions at the legislative level is fixed in Article 212 of the Labor Code of the Russian Federation. Currently, the risk of coronavirus infection and the risk of death exceed an acceptable level (10-6), which causes the mandatory introduction of deterrent measures. Due to the spread of coronavirus infection, the nomenclature of principles for creating safe working conditions includes the prevention of potential infection of employees with COVID-19, the implementation of which is checked by Rostechnadzor and the State Labor Inspectorate in accordance with current regulatory requirements.

2. During the pandemic, employers have faced the problem of effective assessment and management of occupational risks in the workplace. To ensure the safe functioning of the organization, it is necessary to conduct an early and further operational assessment of occupational risk, taking into account epidemiological circumstances.

3. The level of risk of COVID-19 infection may vary within one organization, so a risk assessment should be made for each workplace, taking into account specific working conditions and the presence of actual and potential hazards. In addition, when conducting an individual risk assessment, it is necessary to take into account the probability of a severe disease due to age and the existing diseases.

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Contribution of the authors:

A. N. Lopanov, E. A. Fanina — formulation of the main concept, goals and objectives of the study, calculations, preparation of the text, formulation of the conclusions; O. N. Tomarovchenko, I. V. Prushkovskiy — scientific supervision, analysis of the research results, revision of the text, correction of the conclusions.

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Comparative analysis of engineering solutions against the shift of the upper part of the ladder when performing work at height

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Introduction. Modern construction is characterized by work at a height using stairs. The article presents various engineering solutions aimed at preventing injuries during such work.

Problem Statement. The objective of this study is to compare the available engineering solutions aimed at preventing the upper part of the ladder from shifting when performing work at height.

Theoretical Part. The work shows the ranking of the existing technical means that allow fixing the upper part of the ladder on the surface of the support and reducing the risk of sliding the upper part of the ladder on the support. It is shown that the structure fixed to the support has the least risk in ensuring the safety of work at height.

Conclusion. The article defines the most promising directions of development of technical solutions against shifting the upper part of the ladder.

Keywords: working at height, working on support, working from stairs, stairs sliding, falling from stairs.

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Introduction. In construction, a significant amount of work is performed at height. It is often carried out using ladders. The statistics of industrial injuries in the Russian Federation indicate that injuries when performing work at height account for about 25 % of all industrial injuries in Russia [1]. Most of them are related to construction works using extension ladders [2, 3]. As a rule, when falling from a height, including from a ladder, an employee receives serious injuries, including fatal ones [3, 4]. About 70 % of serious falls from stairs occur using portable ladders, and the most common cause of a fall is the sliding of a ladder under the user [5, 6].

Problem Statement. The cost of purchasing a ladder is small; the ladder is portable, has a low weight and is easy to operate. These things explain the widespread use of various types of ladders in the workplace. The ladder is irreplaceable in those places where there is no possibility for a bucket lift to drive near. In modern conditions of construction production, ladders will be an actual means of lifting to a height (support) for a long time.

When investigating the causes of human falls from ladders, the predominant role of the "human factor" is noted. Therefore, the improvement of technical measures aimed at ensuring the safety of work at height using ladders is relevant within the framework of the occupational risk management system. Safety measures that exclude or minimize the influence of the "human factor" are currently a priority.

In order to ensure the safety of work in mass production, engineering and technical means with a high degree of reliability are widely represented, which are installed on the lower ends of the ladders (metal shackles and pads made of non-slip material). Technical means against shifting the upper part of the ladder when performing work on a support in mass production are very few. At the same time, the available means are not sufficiently effective in all cases.

The aim of the research is to conduct a comparative analysis of engineering solutions against the shift of the upper part of the ladder when performing work on the supports of overhead communication lines (OCL) and overhead power lines (OPL); to determine the most promising directions for the development of technical safety measures against the shift of the upper part of the ladder when performing work on the support.

Theoretical Part. It is possible to ensure the safety of work at height with the use of ladders by increasing stability by using the upper attachments, which are attached to the stairs by a fastening system (Fig. 1).

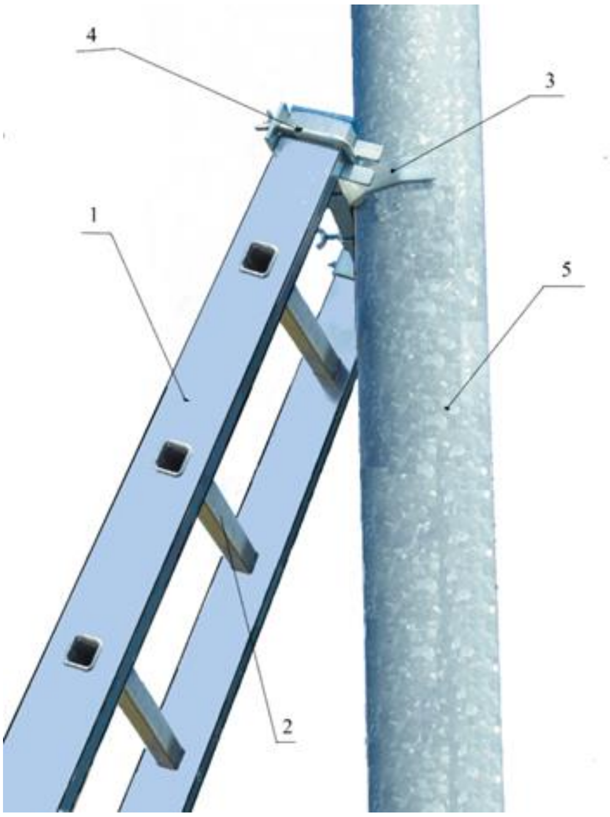


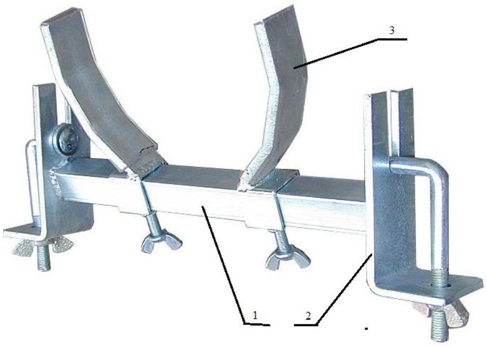
Fig. 1. Installation of a ladder with a nozzle to the support:
1 — ladder string, 2 — step, 3 — attachment,
4 — attachment of the nozzle to the ladder, 5 — support

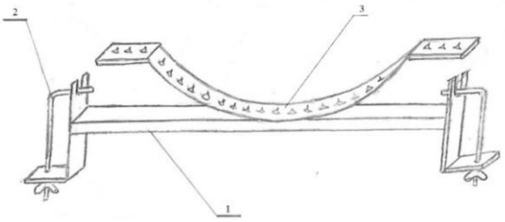
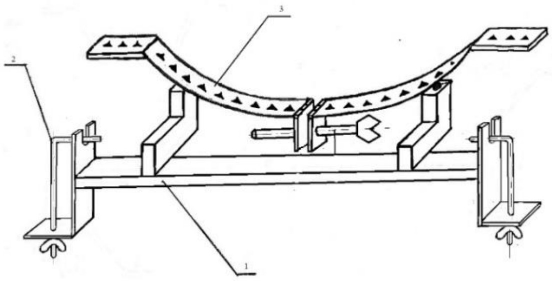
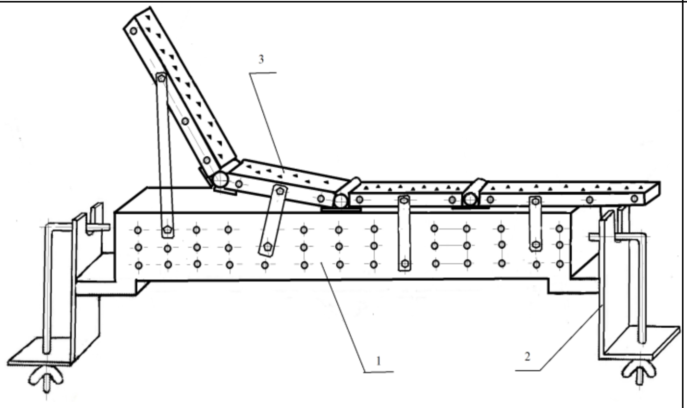
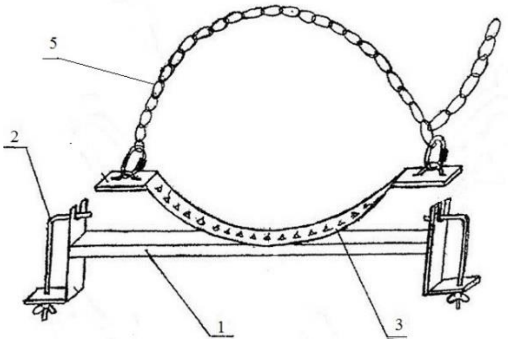
The types of attachments differ depending on the method of coupling with the support, the possibility of adjusting the coupling area, as well as the presence of built-in safety systems when performing work at height.

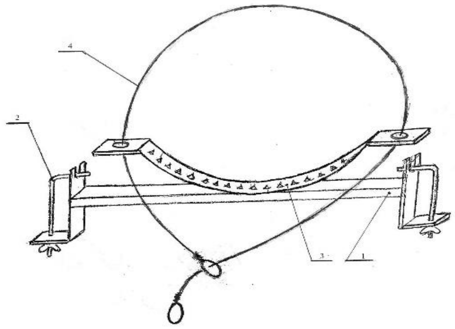
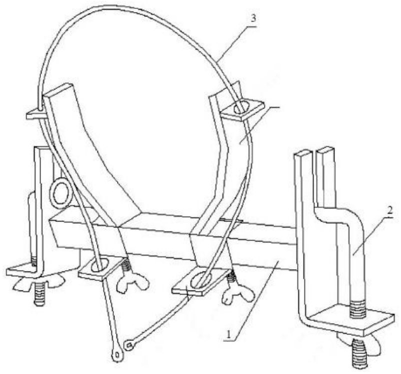
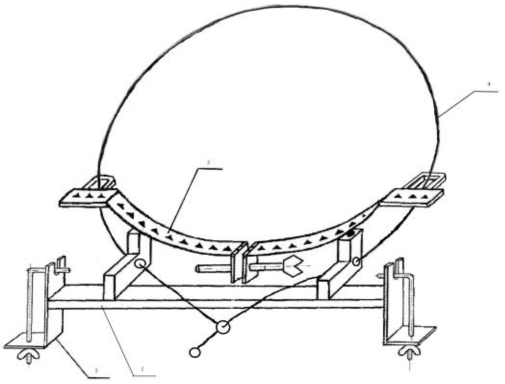
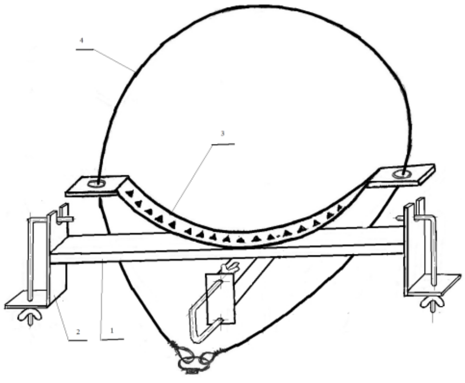
Table 1 shows the available types of attachments, which are grouped by the functional design and the method of coupling with the support [7–14].

Table 1

Attachments and functional design

Name	General view	Patent
1	2	3
Attachments to the ladder with a stop against shifting		Attachment for support on a pole / mast KRAUSE

Name	General view	Patent
1	2	3
		Patent for the utility model "Ladder attachment", Patent number:184480 [8].
		Patent for the utility model "Ladder attachment", Patent number: 193480 [9].
		Patent for the utility model "Ladder attachment", Patent number:202731 [10].
Attachments to the ladder with a stop and a ring chain		Patent for the utility model "Ladder attachment", Patent number:189558 [11].

Name	General view	Patent
1	2	3
Attachments to the ladder with a stop and an anchor loop		Patent for a utility model "Attachment to a ladder with an anchor device", Patent number:196601 [12].
		Patent for a utility model "Attachment to a ladder with an anchor point", Patent number: 185193 [7].
		Patent for the utility model "Ladder attachment", Patent number: 198464 [13].
		Patent for a utility model "Attachment to a ladder with a reinforced attachment for a ladder and an anchor device", Patent number: 202731 [14].
Notation to the figures: 1 — attachment on the ladder, 2 — fixing of the attachment to the ladder, 3 — stop; 4 — anchor loop, 5 — chain.		

The attachment with a stop and a chain will securely fix the upper edge of the ladder to the support. But before you do this, you need to climb the ladder. Since insurance against falling from a height while climbing the ladder is not provided, it is necessary to get it for this time [7,11–14].

Other attachment designs that do not have a rigid attachment to the support, have a reduced degree of safety, which is determined by the coupling force of the attachment, depending on its design [8–10].

The ladder attachment described in [8] is distinguished by its ease of use. The stop has spikes that provide grip with the support. The ladder attachments described in [9, 10] also have a stop with spikes, but the coupling area can be adjusted [15, 16] by changing the radius of the stops relative to the support.

The risk-oriented approach to occupational safety assessment involves the use of various mathematical models and methods that allow comparing risks and choosing the most effective solution [17, 18]. The solution to the problem of ensuring the safety of work at a height on ladders is one of the priorities in labor protection [19].

With a large variety of available engineering solutions that are aimed at improving the safety of work at height using ladders, there is still no universal effective engineering solution. When evaluating samples of equipment at the stage of their development, various engineering solutions can be applied in modern engineering practice, depending on the situations [20, 21].

The development of technical safety measures will minimize the role of the "human factor", reducing the risk of falling ladders from the supports.

Table 2 shows the ranking of technical means that allow fixing the upper part of the ladder on the surface of the support, as the risk of sliding the upper part of the ladder from the support decreases. So, for a ladder without an attachment, the risk of sliding the upper part of the ladder from the surface of the support R_1 will be the maximum, and the engineering solution in the form of an attachment to the ladder with a stop and an anchor loop will provide the minimum risk R_4 of all the proposed engineering solutions.

Table 2

Ranking of technical solutions as the risk of shifting the upper part of the ladder from the support surface decreases

Engineering solution	Ladder without an attachment	Attachment to the ladder with a stop against shifting	Attachment to the ladder with a stop and a ring chain	Attachment to the ladder with a stop and an anchor loop
Risk of slipping off the top of the ladder from the support	R_1	R_2	R_3	R_4
	$R_1 > R_2 > R_3 > R_4$			
Safety measures	There is no stability at the point of contact of the ladder with the support. In the process of climbing the ladder, it is necessary to have an anchor point for fixing the safety system.	The ladder with the attachment is stable against the support. In the process of climbing the ladder, it is necessary to have an anchor point for fixing the safety system.	When climbing the ladder, it is necessary to have an anchor point for fixing the safety system. The ladder is rigidly fixed with a support by means of a chain.	The device includes an anchor point. No additional anchor devices are required for safety when climbing and working at height.

Analyzing the engineering solutions safety, it can be argued that the attachments to the ladder with a stop and an anchor loop ensure maximum safety of the employees through the possibility of using a safety system to create an anchor point at a height without additional technical means. According to the authors, this conceptual direction of the technical solution is the most promising.

Conclusion

1. The article presents a comparative analysis of technical solutions that allow fixing the upper part of the ladder on the support surface.

2. The type of engineering solutions against the shift of the upper part of the ladder when working on a support is determined, which are the most promising from the point of view of ensuring safety when working at height. The ranking is carried out of technical means that allow fixing the upper part of the ladder on the surface of the support, as the risk of sliding of the upper part of the ladder from the support is reduced.

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The state of fire alarm systems at protection facilities from 2016 to 2020

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Introduction. The article presents the results of studies on assessing the performance of fire alarm systems in buildings (structures) for various purposes in the period from 2016 to 2020. The analysis of the regulatory framework and the results of previous studies in the field of assessing the effectiveness of fire automatics, including at industrial and residential facilities, is presented. This article explores other types of protected objects.

Problem Statement. The objective of the research is to study the efficiency of functioning of fire alarm systems.

Theoretical Part. Based on the statistical data for the period from 2016 to 2020 about fires and their consequences, the operability of fire alarms in buildings (structures) for various purposes has been investigated. The social (the number of dead and injured people) and economic (direct material damage) consequences of fires when the fire alarm systems are triggered are analyzed.

Conclusion. The results of the study of the operability of the fire alarm in general indicate an increase in the efficiency of its operation compared to the period up to 2016. At the same time, the number of protected objects is characterized by rather low values (less than 50 %) of response efficiency indicators and significant socio-economic consequences of fires.

Keywords: fire, object of protection, automatic firefighting equipment, fire alarm, operability, efficiency, statistical data, fire accounting card.

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Introduction. In 2020, about 439.31 thousand fires occurred in the Russian Federation, which killed 8310 people, injured 8419 people, and direct material damage amounted to more than 20.8 billion rubles [1].

The largest number of dead and injured people falls on the initial stage of the fire development. At the same time, fires that are not detected in a short time can lead to significant material consequences. In this regard, one of the solutions to prevent significant socio-economic consequences of fires is to reduce the time of fire detection and increase the efficiency of the fire alarm system (hereinafter referred to as FAS), which are the primary elements in the fire protection system of buildings (structures).

Foreign approaches to FAS design at various protection facilities are included in the European regional standards of the EN 54 series and in the international standards ISO7240. Also, the requirements for the design standards and test methods of FAS are included in the standards EN 14604 and ISO 12239. In the Russian Federation, the issues of designing and applying of FAS are determined by the provisions of the codes of rules — SP 484.1311500.2020 "Fire protection systems. Fire alarm systems and automation of fire protection systems. Norms and rules of design" and SP 486.1311500.2020 "Fire protection systems. The list of buildings, structures, premises and equipment subject to protection by automatic fire extinguishing installations and fire alarm systems. Fire safety requirements". In GOST R 53325-2012 "Fire equipment. Technical means of fire automation. General technical requirements and test methods" FAS elements test methods are regulated.

A significant number of publications have been devoted to the research on the effectiveness of triggering and evaluating FAS efficiency at various hazardous locations. Thus, in work [2], the methods for assessing the reliability of fire automation systems are proposed. The approaches to the safety of technological processes with the use of diagnostics of fire detectors are reflected in publications [3–4]. Article [5] discusses the issues of trouble-free operation of FAS at energy facilities based on the reliability function. In work [6], the effectiveness of fire automation operation at production facilities from 2005 to 2014 was studied. According to its results, it was found that only in 77% of cases FAS worked and completed the task; in other cases (23%) the task was not completed.

Articles [7–9] are devoted to evaluating the effectiveness of FAS operation in the residential sector. The data on FAS efficiency from 2005 to 2012 were studied. It was found that FAS installed on residential facilities only fulfilled their task in 36.2% of cases. Accordingly, in the remaining cases (63.8%), FAS did not fulfill their task. In works [9-10], the measures are proposed for the installation of smoke fire detectors in residential buildings, including built-in sound alarms for reducing the social consequences of fires in the housing stock.

The analysis of publications [5–9] shows that studies of the effectiveness of fire alarm activation at residential and industrial facilities were conducted on the basis of statistical data generated before 2014.

The results of research on FAS efficiency from 2016 to 2020 at residential and industrial facilities are given in publications [11–12]. Thus, in article [11] it is noted that the efficiency of FAS operation in residential buildings has increased significantly and from 2016 to 2020, on average, it was 83.1% for single-family residential buildings, and for multi-apartment buildings — 75.7%. A similar situation with an increase in the efficiency of fire alarm operation is observed at industrial facilities [12].

The above analysis of literary sources shows that specialists in the field of fire automation in their research focused on the study of a certain group of hazardous facilities. Mainly industrial objects and residential buildings were considered. Other types of buildings (structures) were not considered and fell out of the field of view of researchers. In this regard, it is advisable to analyze FAS performance at other hazardous facilities. This study will allow us to assess FAS performance on a wider range of hazardous objects with different functional purposes.

Problem Statement. The task of the study is to analyze the state of FAS operability at various hazardous facilities from 2016 to 2020. As hazardous facilities, industrial buildings, warehouse buildings (structures), buildings (structures) for storing cars and other wheeled vehicles, places for storing substances (materials), farmland and other open areas, residential buildings, agricultural buildings (structures), buildings (structures) under construction (reconstruction), industrial buildings (installations), vehicles, buildings (structures) of trade enterprises, educational buildings, buildings of health care and social services, buildings of service maintenance, administrative buildings, buildings (structures) for cultural and leisure activities and religious rites, buildings for temporary stay (residence) of people, other buildings (structures).

Theoretical part and the results of the research. To solve this problem, two calculation methods are proposed for evaluating the effectiveness of FAS operation. The first method is based on the analysis of various modes of FAS operation ("it worked and completed the task", "it did not work and did not complete the task", "it was disabled"). The second method is based on determining the social and material consequences of fires, taking into account the operation of the fire alarm system.

The description of the proposed methods and the corresponding calculated dependencies are given in publications [11–12]. The initial information for the calculations was the data of the federal state information system "Federal Data Bank "Fires" [13].

The following results of the assessments of the performance of FAS on various hazardous facilities were obtained.

Figure 1 shows data on changes in the performance of FAS for all hazardous objects from 2016 to 2020. The average value of the efficiency of FAS for all hazardous objects for the period under review was 85.9%. The highest value (86.9%) was observed in 2020, the lowest (85.1%) — in 2017.

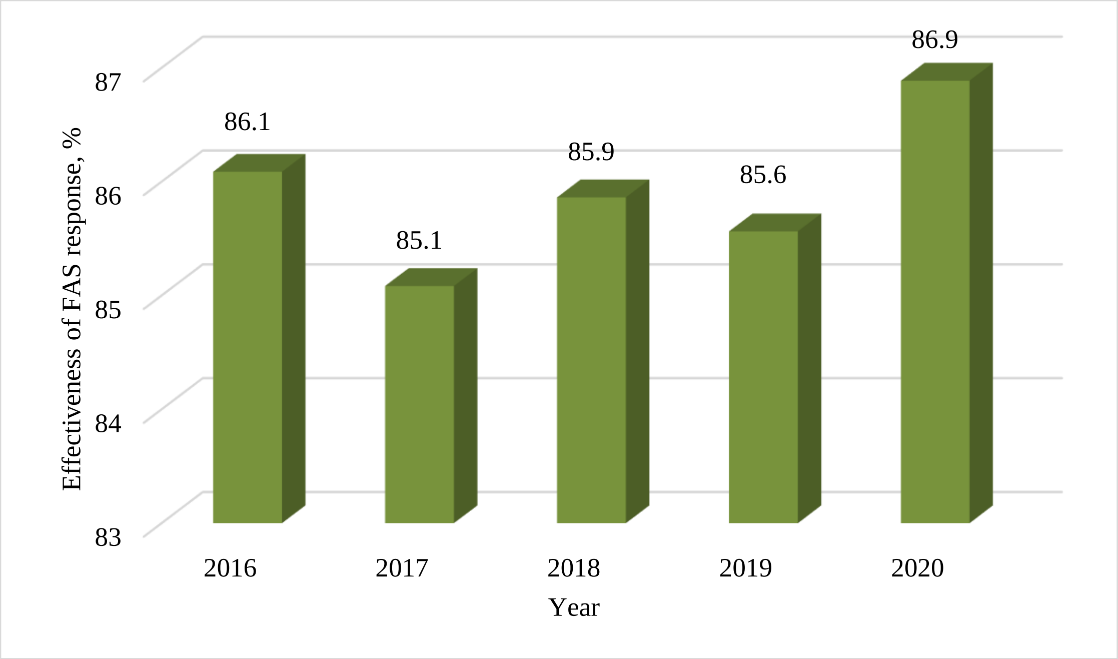

Fig. 1. Change in FAS effectiveness from 2016 to 2020

Figure 2 shows the data on FAS efficiency for different types of buildings (structures) from 2016 to 2020. The highest efficiency of FAS operation was registered at industrial facilities (installations) — 91.4%, as well as at buildings (structures) for storing cars and other wheeled vehicles — 90.3%. The lowest efficiency of FAS operation is characteristic of places of open storage of substances (materials), agricultural land and other open areas — 41.9%.

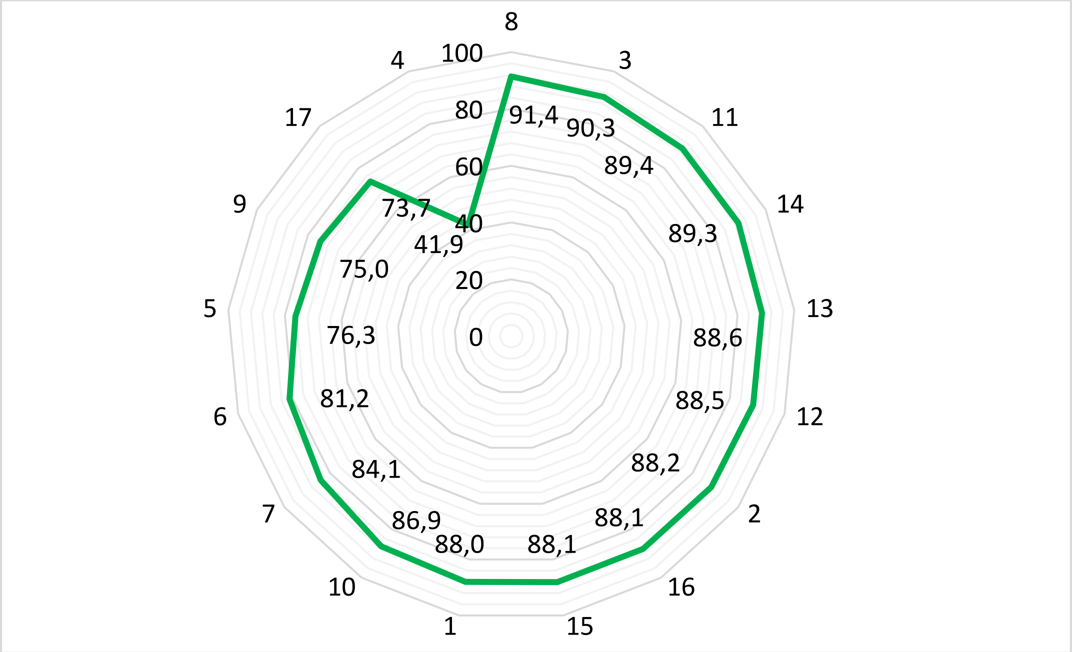

Fig. 2. FAS efficiency by type of hazardous objects

The number on the diagram corresponds to the following types of hazardous objects: 1 — industrial buildings, 2 — warehouse buildings (structures), 3 — buildings (structures) for storing cars and other wheeled vehicles, 4 — places for storing substances (materials), agricultural land and other open areas, 5 — residential buildings, 6 — agricultural buildings (structures) , 7 — constructed (reconstructed) buildings (structures), 8 — constructions (installations) for industrial use, 9 — vehicles, 10 — trade buildings (constructions), 11 — educational purpose buildings, 12 — healthcare and social services buildings, 13 — service buildings, 14 — administrative buildings, 15 — buildings (structures) for cultural and leisure activities and religious rites, 16 — buildings and premises for temporary stay (residence) of the people, and 17 — other buildings (structures)

The calculated data for the indicator "the number of victims (dead and injured) per fire" for those cases when FAS worked and gave a fire alarm are shown in Fig. 3. The smallest number of victims when fire automation devices are triggered is observed at industrial facilities (installations) — 0.016 people per one fire, or one victim per 64 fires, as well as for buildings (structures) of trade enterprises — 0.023 people per one fire, or one victim per 44 fires. Most of the victims are observed in fires in residential buildings — 0.218 people per one fire, or one victim per 5 fires.

The calculated data for the indicator "direct material damage per fire" for those cases when FAS triggered and gave a fire alarm are shown in Fig. 3. The greatest direct damage from fires was registered for warehouse buildings (structures) — 13.7 million rubles per fire, as well as for agricultural buildings (structures) — 11.4 million rubles per fire. The least direct damage from fires was registered for buildings (structures) under construction (under reconstruction) — 58.7 thousand rubles per fire, as well as for buildings, structures for storing cars and other wheeled vehicles — 84.0 thousand rubles per fire.

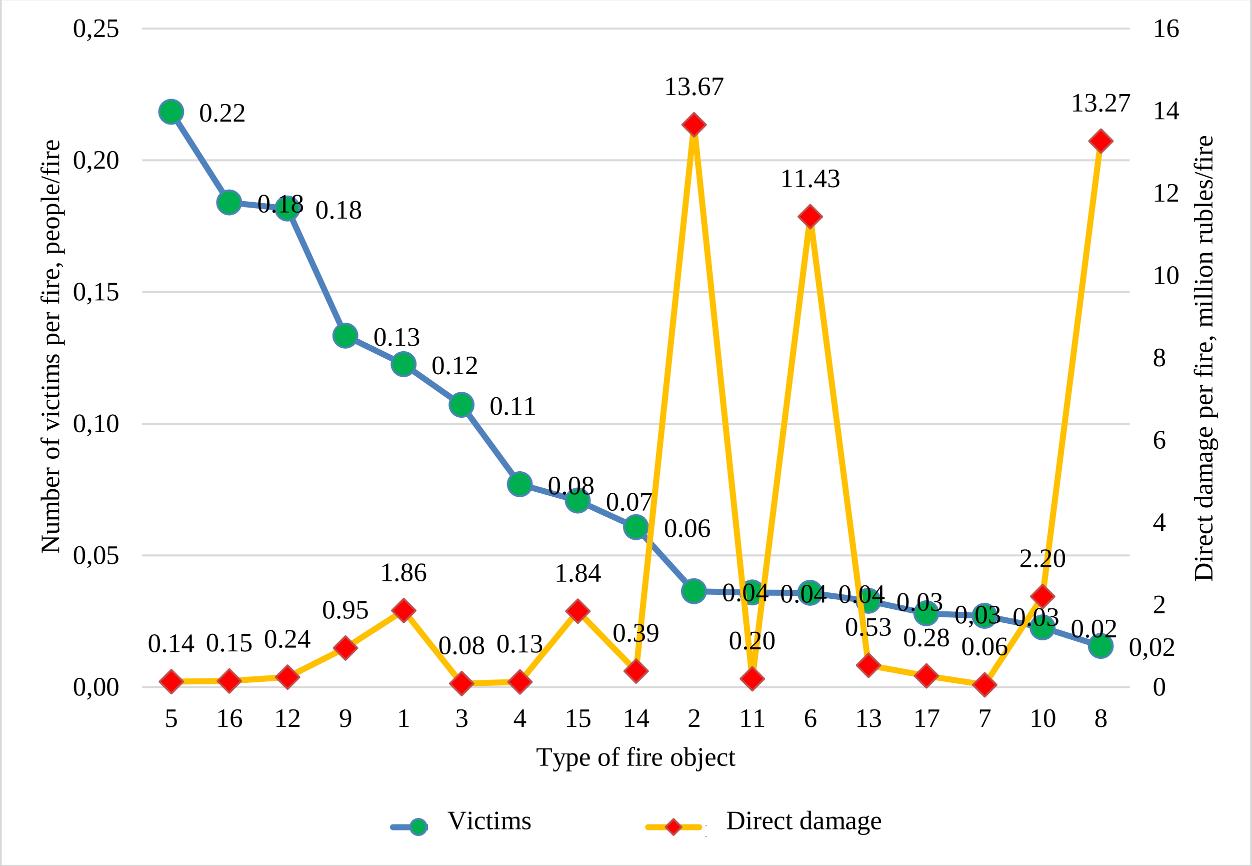

Fig. 3. Number of victims and direct material damage per fire by type of hazardous objects. The number on the abscissa axis corresponds to the type of hazardous facilities shown in Fig. 2.

Conclusion. The study of FAS efficiency at various hazardous facilities from 2016 to 2020 showed the following. Compared to the previous period (until 2016), the effectiveness of FAS operation at many hazardous facilities has significantly increased. The average value of FAS efficiency for all hazardous objects is now 85.9%. The highest efficiency of FAS operation was noted in industrial structures (installations) (91.4%) and in buildings (structures) intended for storing cars and other wheeled vehicles (90.3%). The lowest efficiency of FAS operation is observed in places of open storage of substances (materials), on agricultural land and other open territories (41.9%). The largest number of victims was noted in fires in residential buildings (on average, one victim per 5 fires), despite the fact that FAS worked and gave a fire alarm. The greatest direct damage from fires was caused to warehouse buildings (structures) — 13.7 million rubles per fire, as well as buildings (structures) for agricultural purposes — 11.4 million rubles per fire).

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A. A. Poroshin — formulation of the concept of the article, the goals and objectives of the study, preparation and analytical review of the literature, calculations, preparation of the text, formulation of the conclusions; A. A. Kondashov — calculations, analysis of the results, preparation of the figures; V. I. Sibirko — preparation of the initial data for the calculation, formulation of the conclusions; V. S. Goncharenko — preparation of the initial data for the calculation.

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Experimental studies of the properties of metal dust

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Introduction. The issues of ensuring the environmental safety of metalworking industries are still very relevant. Moreover, the primary role in these issues is played by the protection of atmospheric air from the emissions of industrial enterprises in this industry. For the successful implementation of measures aimed at ensuring the environmental safety of atmospheric air, it is important to study in detail the composition and properties of the emission components.

Problem Statement. The aim of the study is to analyze the entire range of modern methods for measuring the parameters of the properties of metal dust, as the main component of emissions from metalworking industries; to select the method of experimental research; to conduct a dispersion analysis of metal dust particles.

Theoretical Part. As a rule, the productivity of experimental studies of the parameters of the properties of pollutants largely depends on the methods that were used in the performance of the work. To solve these problems, the authors have analyzed modern methods for measuring the parameters of the properties of metal dust. The choice is made according to the basic principles: relativity, relevance, completeness, labor intensity. The conditions for the final results of the research, their accuracy and reliability, the conditions for the terms, resources, technical means of research used, and the positive and negative aspects of each of the methods under consideration are also taken into account.

Conclusion. The article presents the result of the choice of the research method and the results of experimental studies of the properties of metal dust.

Keywords: metalworking, metal dust, dust properties, property parameters, dispersion composition, microscopic method, dispersion analysis.

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Introduction. Currently, humanity faces a number of problems, among which the problems of ensuring environmental safety occupy a special place. Meeting the needs of modern society has led to the rapid development of all industries, which has significantly affected the quality of the environment [1].

As numerous studies in the field of environmental safety of urban areas show, the development of some industries leads to particularly destructive consequences. Being a natural resource user, a person brings changes to the environment, negatively affecting its natural processes. Therefore, not only the development of industrial production is extremely important, but also the simultaneous rational use of natural resources and environmental protection [2].

Analyzing the features of the production activities of enterprises, it can be concluded that among the main sources of environmental pollution, there are enterprises of ferrous and non-ferrous metallurgy, fuel and energy complex, mechanical engineering and metalworking [3]. Such enterprises cause significant damage to atmospheric air. As a result of emissions of pollutants, there is a gradual change in the composition of the atmosphere, an increase in the amount of carbon dioxide and dust. Concentrated in the lower layers of the troposphere, industrial emissions significantly increase the background air pollution of cities.

Metal dust near the metalworking industry enterprises is the component of background air pollution, which is very dangerous for human health [4]. The formation and release of metal dust at such enterprises are associated with the peculiarities of the implementation of technological processes. As an example, the authors consider the metalworking production, which produces extruders and bag-making machines. The gross emission of pollutants at this enterprise amounted to 7,483 tons/year. According to the results of the inventory, 21 items of pollutants entering the atmospheric air were identified. The need to ensure environmental safety at this enterprise was a prerequisite for further research.

Problem Statement. The production site of the metalworking enterprise was taken for the research, which gave the maximum amount of pollutants, namely, metal dust. The formation and release of metal dust occurs from a number of cutting and grinding machines when separating metal particles from the total amount of technological raw materials (metal sheets and pipes). Since metal dust is the main object involved in the process of air pollution, it is important to study its properties. At the same time, the properties of metal dust undergo qualitative and quantitative changes during the entire process of air pollution [4].

Metal dust is an aerosol of a two-phase system consisting of a dispersed phase (solid metal particles) and a dispersed medium (air medium). The size of solid particles of metal dust varies significantly and can reach 300 microns. According to the division accepted in the literature, particles with a size of less than 1 micron are classified as fine dust, with a size from 1 to 10 microns — as medium-dispersed, with a size of 40 to 140 microns — as coarse. There is also a subgroup of very large dust with a particle size of more than 140 microns. This division into subgroups allows us to characterize the dispersed composition of metal dust, its mass and quantity.

The following groups of dust parameters are distinguished:

1) physical-chemical:

— aggregate state — solid;

— color — dark gray;

— resistance to high temperatures (melting point at a pressure of 101.3 kPa — 1565°C);

— density at 20°C — 5240 kg/m^3

— heat capacity at 0°C — 113.91 J/(mol×K);

— bulk density ρ = 1920 kg/m^3;

— breaking strength of the layer — 300-600 Pa;

2) hydrodynamic:

— solubility in water — insoluble at 25°C;

— wetting angle — 45%.

Chemical properties of metal dust include its chemical composition, toxicity, explosion and fire hazard. The lower concentration limit of ignition (LCLI) of iron oxides is 105 g/m^3. Dusts with an LCLI of more than 65 g/m^3 are classified as fire-hazardous [5].

Theoretical Part. At the initial stage, to solve the problem, the authors identified the most significant property of metal dust — its dispersed composition. The choice of a particular method for capturing and cleaning emissions containing metal dust depends on the size of the particles and their quantity. Depending on the size of the metal dust particles, the efficiency of the designed cleaning system can be reduced by up to 40%.

When determining the measurement method, the authors have made a choice based on the principles of relativity, relevance, completeness and labor intensity.

For comparison, the following methods for determining the dispersed composition of dust particles were chosen: sieve, microscopic, sedimentation and hydrodynamic [6]. The most acceptable of them is the microscopic method. The advantages of this method are the possibility of determining the geometric parameters of metal dust particles, considering the structure of the surface, structure and shape. It is important that when using the microscopic method of research, particle measurement can be carried out in the range from 0.3 to 100 microns. However, electron microscopes with higher accuracy are often used to determine the size of metal dust particles less than 1 micron.

As a disadvantage of the microscopic method, its considerable labor intensity should be noted. Accurate results of determining the dispersed composition can be obtained only by studying several hundred particles. This explains the long duration of experimental studies. To reduce the time for processing the measurement results, computer technologies were used to determine not only the average size of metal dust particles, but also to set the parameters of the distribution law.

Thus, the chosen method of experimental studies of the dispersed composition of metal dust meets a number of requirements:

— the positive aspects of the method under consideration prevail;

— there is data on such analyses, the samples under study;

— the conditions for the time, resource and technical means required for the analysis are feasible;

— the requirements for the final indicator of research and the reliability of the results are provided.

When conducting the experimental studies, the method of microscopic analysis was used [7]. Table 1 presents preliminary theoretical results of the size distribution of metal dust particles.

The median diameter d_{50} characterizes the dispersion of aerosols, that is, the particle size by which the aerosol mass is divided into two equal parts. At the same time, the mass of particles smaller than d_{50} is 50% of the total mass of metal dust, as well as the mass of particles larger than d_{50} [5].

As a result of the conducted studies, the median diameter was d_{50}=35 microns.

The specific surface area of the particles equal to 560 m^2/kg and the suspension velocity $\nu_{вит}$ = 0.5–9 m/s are also determined.

Table 1

Distribution of metal dust particles by size

Particle size at the fraction boundaries, σ, microns	5	15	25	35	45	55	65	75	85	95
Fractions, D, % of the total mass of particles	4.75	8.02	2.78	8.18	7.04	7.86	16.37	26.51	11.62	6.87

Let us consider the form in which the results of the analysis of variance are displayed.

When constructing an integral graph of the distribution of the sizes of metal particles, the most voluminous fractions of particles (Q) that have a size smaller than the current one are deposited on the ordinate axis (Fig. 1). Therefore, the integral distribution curve can be represented as a certain function Q=f(d).

In the case of a granulometric graph, the linear size (d) of the measured particles is transferred along the abscissa axis.

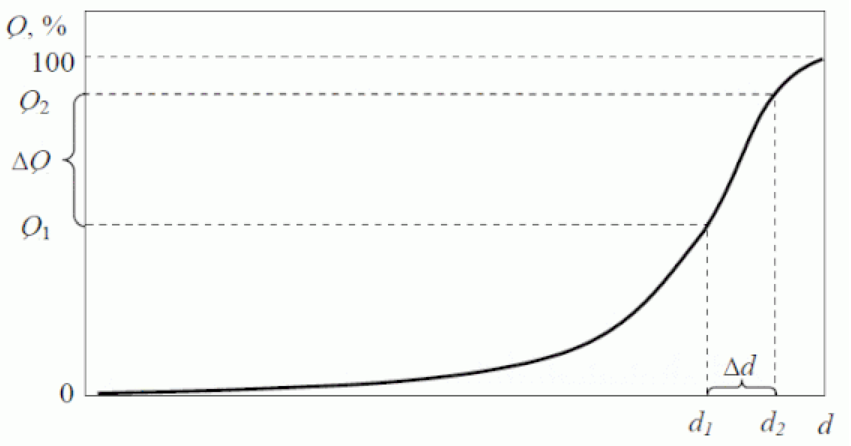


Fig. 1. Integral curve of particle size distribution [8]

When determining the volume fraction of metal dust particles with a size less than d_1, it is necessary to identify the size of d_1 on the lower scale and draw a vertical line from this point to the intersection with the integral distribution curve. The value of the ordinate of the obtained point will represent the volume fraction occupied by metal dust particles with a size less than d_1, in this case it is Q_1. At the same time, there is a correspondence between the size interval from d_1 to d_2 and the volume fractions from Q_1 to Q_2 [9].

To obtain a series of intervals ΔQ_i, we divide the integral curve along the abscissa axis into intervals. We construct ordinates for the points of intersection of vertical lines with an integral curve.

Moreover:

$$\sum_{i=1}^{N} \Delta Qi = 100\%, \tag{1}$$

where N — the number of selected intervals (fractions) of particle sizes.

The intervals of volume fractions are represented as columns with height Fi=ΔQi. Thus, a differential histogram of the distribution of metal dust particles by size is constructed (Fig. 2).

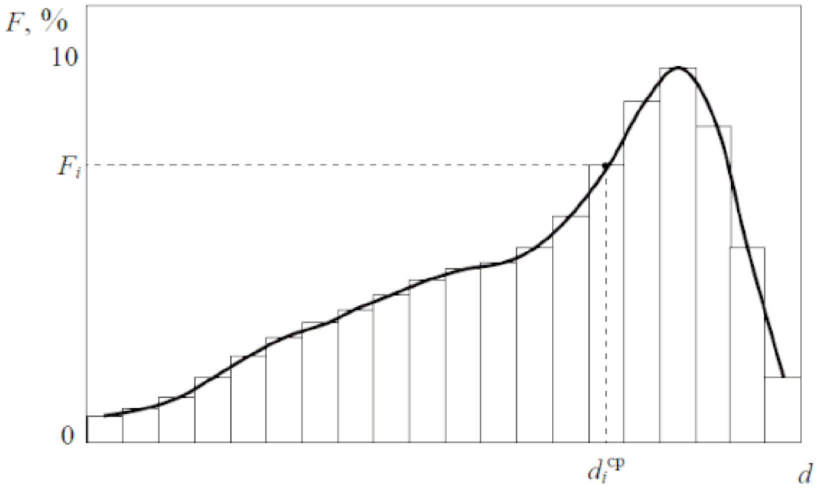


Fig. 2. Particle distribution on the differential histogram [8]

When connecting the upper part of the columns of the differential histogram of the distribution, we get a smooth differential curve. Such a curve means that particles with average sizes located in the middle of one column (d_{icp}) occupy F_i, % by volume in the measured mass.

When constructing a differential distribution curve, the ratios $\Delta Q_i/\Delta d_i$ are often marked instead of the intervals of volume fractions F_i. The area of each rectangle corresponds to the content of the fraction of the material in certain interval sizes Δd_i.

To determine the most probable diameter ($d_{н.в.}$) in the considered dispersed system, it is necessary to construct a differential distribution curve and connect the midpoints of the upper parts of the rectangles with a smooth line (Fig. 3).

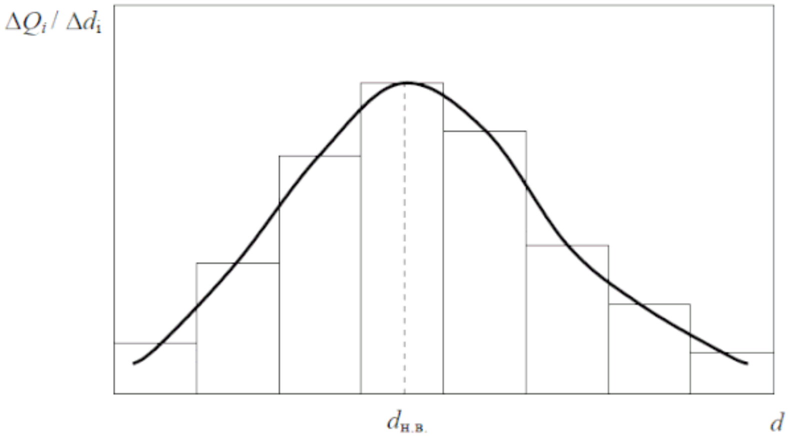
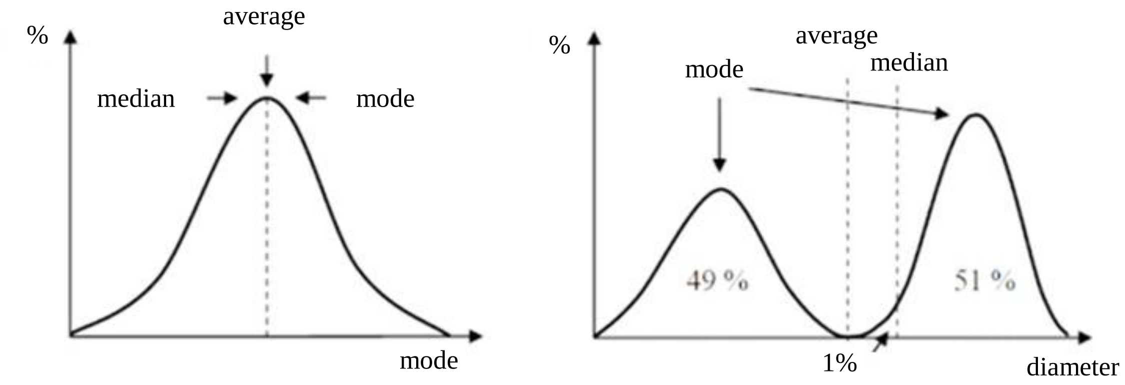


Fig. 3. The most probable diameter of metal dust particles [8]

As a rule, the main statistical indicators of the differential curves of the particle size distribution are the average value, mode and median of the distribution (Fig. 4).



a) *b*)

Fig. 4. Basic statistical characteristics for normal or Gaussian (a) and bimodal (b) particle size distribution [8]

The average value is the average particle size, the result of averaged data.

The mode is the position of the maximum of the differential distribution curve, or the most likely particle size in the population.

Three statistical indicators coincide in the case of a normal distribution (Fig. 4a). However, with a bimodal distribution, the average is between two distribution intervals (Fig. 4b). There are also no particles with a diameter equal to the average. The median diameter is shifted to the right side of the distribution. The differential curve has two pronounced maxima (two modes). The largest mode corresponds to the position of the maximum of the right part of the distribution [10].

The results of microscopic analysis and the results of calculations are presented in Tables 2 and 3.

Table 2

Results of microscopic analysis

Particle diameter σ, microns	Number of particles					
	I field	II field	III field	IV field	V field	Number of particles in all fields N
5	10	12	7	-	-	29
15	9	-	6	14	20	49
25	6	8	3	-	-	17
35	16	-	-	11	23	50
45	-	15	7	21	-	43
55	8	11	1	12	16	48
65	20	31	14	20	15	100
75	32	20	37	33	40	162
85	31	14	8	18	-	71
95	14	11	-	17	-	42
ΣN =611						

Table 3

Data for constructing an integral curve for the distribution of the number of particles by size

Particle diameter σ, microns	Number of particles of the fraction N	Percentage content Fraction Q, %	Increasing total content of fractions D, %
5	29	4.75	4.75
15	49	8.02	12.77
25	17	2.78	15.55
35	50	8.18	23.73
45	43	7.04	30.77
55	48	7.86	38.63
65	100	16.37	55
75	162	26.51	81.51
85	71	11.62	93.13
95	42	6.87	100
	ΣN =611	ΣQ=100	

Below is the information for constructing a differential distribution curve obtained by processing the integral curve (Table 4).

Table 4

Data for constructing a differential curve for the distribution of the number of particles by size

σ, microns	5	15	25	35	45	55	65	75	85	95
Δσ, microns	5	10	10	10	10	10	10	10	10	10
ΔQ,%	4.75	8.02	2.78	8.18	7.04	7.86	16.37	26.51	11.62	6.87
ΔQ/Δσ	0.95	0.80	0.28	0.82	0.70	0.79	1.64	2.65	1.16	0.69

The integral distribution curve constructed according to Table 3 is shown in Fig. 5.

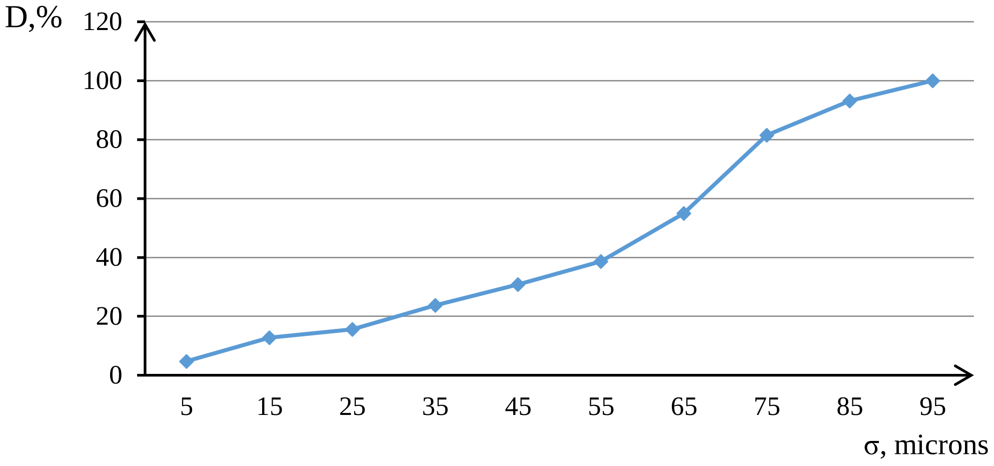


Fig. 5. The integral distribution curve of particles by size

According to Table 4 and the differential curve constructed from it (Fig. 6) it is obvious that its maximum falls on 75 microns.

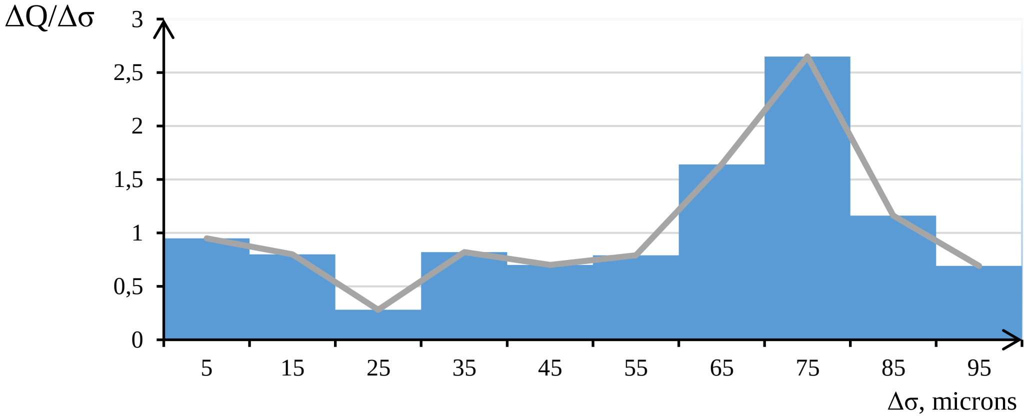


Fig. 6. Differential curve of particle size distribution

Particles of irregular granular shape with the inclusion of metal chips. Particle faces with jagged edges [7, 9, 11].

Conclusion. The analysis of the experimental research methods used to determine the dispersion composition of metal dust particles allowed us to choose the microscopic method that suited best the tasks set. According to the experimental data obtained, it is clear that particles with a size of 75 microns predominate in the total mass of metal dust. Therefore, the metal dust formed during cutting and grinding can be attributed to the medium-dispersed. The conducted research allows us to proceed further to the consideration of the most promising methods and ways for ensuring environmental safety at metalworking enterprises.

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Contribution of the authors:

L. V. Dikova — determination of the purpose and objectives of the study, analysis, preparation of the text, formulation of the conclusions; N. S. Samarskaya — formulation of the concept of the article, selection of the topic, scientific supervision, analysis of the results, revision of the text.

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Development of technique of remote spectral sensing of technogenically loaded territories

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Introduction. The article considers the problem of monitoring technologically loaded landscapes. To solve it, the authors proposed an innovative method for studying the chemical composition of objects using direct spectral sensing means.
Problem Statement. The objective of this study is to consider the possibility of using spectral sensing to control the composition of soils in technogenically loaded territories.
Practical Part. To confirm the hypothesis that observing changes in the parameters of reflection spectra in non-selective areas will make it possible to establish the presence of basic biogenic macroelements for plants in the soil and evaluate its fertility, or determine the degree of contamination of the territory, a laboratory experiment was conducted using modern spectral equipment and multidimensional data calibration was performed.
Conclusion. The results of the analysis show the fundamental possibility of using spectral sensing in the monitoring of technogenically loaded territories using methods of multidimensional data analysis.

Keywords: monitoring, direct spectral sensing, soil chemistry, multivariate data analysis, state indices.

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Introduction. Over the past few years, man-made soil disturbances have reached unprecedented proportions as a result of the expansion of urbanized territories and the action of other anthropogenic factors. According to the State Report on the State and Environmental Protection of the Russian Federation for 2019, the area of disturbed land increased by 4.5 thousand hectares compared to 2018 and amounted to 1076.9 thousand hectares [1]. The report also notes the fact that over the past ten years there has been a tendency to increase the violation of land designated for industrial and other purposes (since 2010 there has been an increase of 119.9 thousand hectares). Thus, the organization of a monitoring system for territories near objects with a high technogenic load in order to control the quality of the environment and prevent possible degradation of the soil cover is an important and relevant topic at the moment.

The main problem of monitoring technogenically loaded territories today is to obtain objective and timely information about their condition.

There are field and laboratory methods of soil research [2]. Despite the fact that field methods are applied directly on the spot, they have a large measurement error, which does not allow us to correctly assess the quality of soils. That is why in most cases, the control of the state of the soil cover is carried out by a natural method with sampling and their examination in laboratory conditions. Laboratory research methods are quite accurate, but time-consuming. This method, as well as the field method, has a number of disadvantages, since for a real assessment of the soil cover of the territory, continuous recording of its state in real time is necessary. This is due to several things. Firstly, in areas with a high anthropogenic load, a sharp increase in toxicants in the soil cover is possible, the duration of generation of which may be much less than the interval between measurements. Secondly, laboratory studies require such work as taking a sample, transporting it to an accredited laboratory, directly analyzing and processing the data obtained, the output result may differ significantly from reality. And, thirdly, a reliable assessment of the total pollution flows is possible not by individual values of a number of observations, but by the integral of the controlled parameter over time.

The main advantage and feature of direct spectral sensing in comparison with the known methods is the study of the composition, structure and properties of objects at the research site without any preliminary operations [2]. Measurements can be carried out remotely by installing the equipment on any type of mobile platform or from the operator's hand. Spectral sensing is the basis for the creation of optical multi-sensor systems (MSS). MSS operate in a wide spectral range, which, when used, makes it possible to isolate specific spectra of soil reflection. This will allow optimizing the work on the removal of spectral characteristics and adjusting the monitoring process to the solution of specific tasks for the detection of a certain substance [3].

The idea of spectral sensing is that each chemical substance has its own spectral characteristics [3]. Observation of changes in the parameters of the soil reflection spectra will allow us to determine the presence of the main biogenic macronutrients for plants in the soil and assess its fertility. It is possible to determine the degree of contamination of the territory when detecting toxicants. The detection of individual substances by spectral sensing will also help to formulate the properties inherent to a particular soil under study, and to make a step-by-step description of the process of its self-purification after technogenic pollution.

Due to its significant advantages in comparison with other methods, the method of direct spectral sensing was chosen for monitoring and controlling technogenically loaded territories, the possibility of applying it in practice is considered in this article.

Problem Statement. The objective of this study is to consider the possibility of using remote spectral sensing to monitor the state of technogenically loaded territories.

The spectral characteristics depend on the composition of the soils. Since this technique is being developed for highly loaded technogenic landscapes, the analyzed samples taken for the experiment should correspond in their composition to the composition of the soils of such territories.

Initially, an assessment of the main elements that the soils of such landscapes can contain was carried out. Chemical indicators characterizing the properties of most soils were selected. Organic carbon was determined as a sign of soil humification, responsible for the presence of organic matter. Nitrogen in two types (nitrate and nitrite), sulfur and phosphorus were isolated as the main biogenic macronutrients necessary for the reproductive ability of plants. Potassium and sodium were taken into consideration as the main soil electrolytes. The ash content, which is responsible for the inert component of the soil cover, and humidity, which affects the spectral characteristics of soils, was also determined [4].

For the purposes of the research, the territories of agricultural lands located in the area of settlements of the Samara region were selected: Bolshaya Chernigovka, Kinel-Cherkasy, Rozhdestveno, Sergievsk and Khvorostyanka. Soil samples from the territories near the city of Togliatti that are not used for agricultural needs were also examined. At the sampling points of these samples, an increased content of phosphorus and nitrogen is observed due to man-made pollution. It is due to the close location of the existing enterprises (TolyattiAzot, KuibyshevAzot) and the currently liquidated plant Fosfor.

The initial data set on the chemical composition of the listed soils was created based on the results of quantitative and chemical analysis (QCA) of the laboratory of the Scientific and Analytical Center for Industrial Ecology of SamSTU.

Theoretical Part. A calibration database was created to build a regression model that can determine the content of chemical elements in the soil. The calibration data included the entire set of samples with previously clarified indicators, which will later allow determining the concentrations of real samples using the model.

An experimental setup was assembled to obtain the spectral characteristics of the samples. It included a portable computer with OceanView software, a USB cable for connecting a spectrometer, an incandescent light source, miniature OceanView STS-UV(UV) and STS-NIR (near-IR) spectrometers, a fiber-optic probe or collimator.

The installation used miniature spectrometers with different study ranges. The STS-UV spectrometer was used for taking reflection spectra in the ultraviolet radiation range (190-650 nm) and STS-NIR for near-infrared radiation (650-1100 nm). With this combination of spectrometers, it becomes possible to obtain spectra in the range from ultraviolet to near infrared, which completely cover the entire visible range. The equipment allows you to register a spectral signal, process it and display the results as a graphical representation on a computer monitor. These models of compact spectrometers are chosen as one of the most compact, and, therefore, suitable for installation on any type of mobile platform or for working in the field with the operator's hands device [5]. The use of two spectrometers made it possible to further conduct their comparative analysis and find out the range of the spectrum, where the response of the parameters under consideration is more clearly recorded.

A miniature spectrometer was connected to a fiber-optic probe. The probe technique is used for the convenience of taking readings at a remote distance from the spectrometer in the contact mode [6].

The advantage of such a technique is the use of a standardized lighting source without the influence of external sources. The probe has several main disadvantages: it increases the cost of installation, requires power for the lighting source, and requires close contact with the studied material. This makes it difficult to use it widely. Nevertheless, its use for research purposes is quite justified.

The system with a probe is replaced by a collimator for use in the field as a means of contactless or remote sensing. An optical collimator is a lens (in the simplest case, a concave mirror), in the focal plane of which is the matrix of the spectrometer. This arrangement makes it possible to obtain approximately parallel radiation beams. The spot from which the reflection spectrum is taken does not increase when the spectrometer moves away from the sample surface. In this case, a broadband incandescent lamp is used as a radiation source. It gives an almost uniform radiation power over the entire studied range. The radiation source was placed to the side of the sample location at a distance of about 10 cm, just like the spectrometer itself. The angle between the axes of the incident radiation and the collimator was 45 degrees, which simulates the position of the sun during field work.

The reflection spectra were recorded from each sample placed on a flat surface in an air-dry and wet (under a layer of water 1 mm thick) space. This made it possible to simulate the operation of the spectrometer at the time of precipitation. The spectral brightness of soils largely depends on their composition, which determines both the size of the particles composing the soil and the possible level of moisture content. An increase in soil moisture leads to a decrease in its reflectivity in the entire spectral range of reflected radiation [7].

The examples of the obtained spectra for different sites are shown in Fig. 1 and Fig. 2.

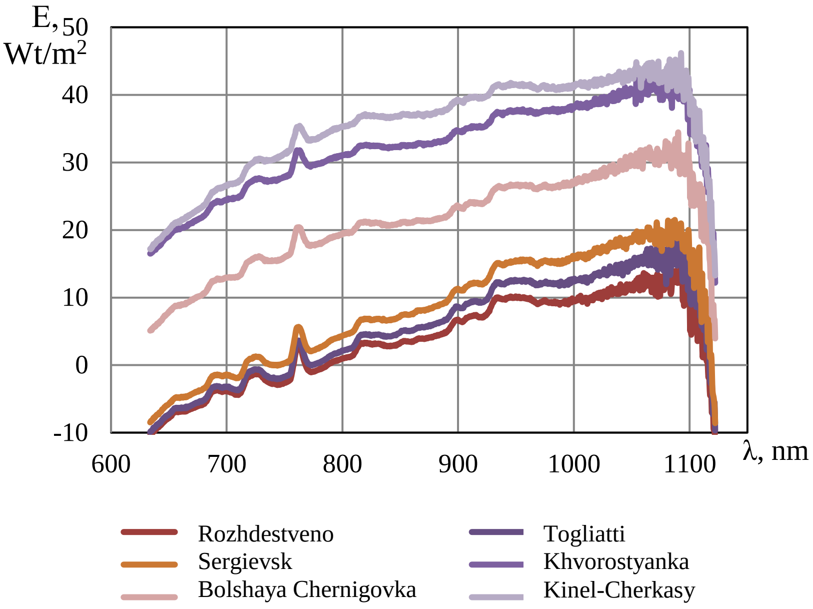

Fig. 1. Spectra of the studied samples from different sites, taken in the NIR range

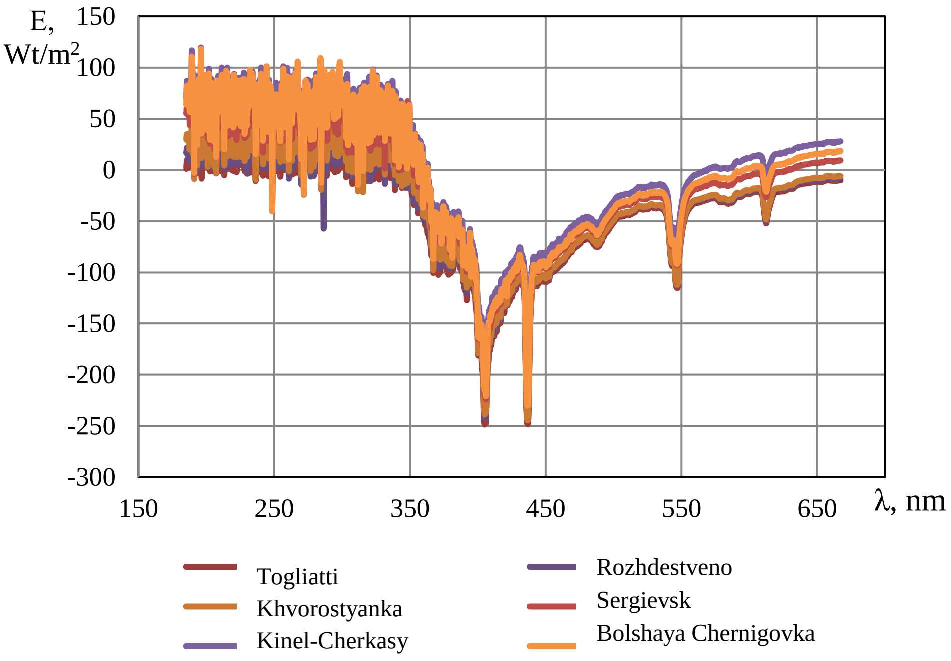

Fig. 2. Spectra of the studied samples from different sites, taken in the UV range

Since during the laboratory experiment it was possible to remove clear spectral curves, presumably characterizing the elemental composition of soil samples, and to obtain some generalized model of the state of the studied samples, the next stage of the work was to assess the possibility of using such a research method in practice in the field. Due to the fact that the laboratory analysis of soils took a long time, and the deterioration of weather conditions did not allow unhindered work in the field, it was decided to use the same soil samples for these works as in the preliminary laboratory experiment. The studied samples were placed on an testing site in the open air. To do this, the sample was rolled out on a site of about 0.25 square meters, and then the spectrum was taken in the same way as at the laboratory stage. At the same time, the reflection spectrum was influenced by weather conditions and the position of the sun.

Then the cross-validation procedure was performed [8]. That is, the spectra were cross-validated on full-scale soil samples under real conditions with 1/5 segmentation. As a training set, an array of data from laboratory studies of the spectral characteristics of soil samples was taken. A segment of 20% of the total number of samples was examined as unknown samples, and an assessment of the coincidence with the existing model was carried out.

Cross-validation refers to statistical methods that are used to evaluate the application of a model method in real conditions. Validation is usually used to compare theoretical data with practical data, because it is easy to understand, easy to implement, and leads to a reliable estimate, which usually has a lower bias than other methods. Its main advantage is working with the existing samples without the need for sampling.

The reflection spectra were recorded from every fifth sample of the studied soils, and a separate set of spectra was formed. Then the procedure was repeated with the second samples in each five. And so on for the formation of five independent sets.

When working on sites, there was no need to adjust for brightness, since the captured spectra were normalized. The integration time was also specially selected to ensure the optimal position of the spectral curves. In addition, software standardization was actually carried out, which significantly reduced the interfering influence of the environment.

As a result, the spectral characteristics of the samples were obtained, which were then compared with the previously obtained laboratory values.

In order to reduce the spread of the results of the spectra taken from the soils at the model sites, the cross-validation cycles were carried out with different partitions, and the obtained values were averaged.

When comparing the captured spectra in the laboratory and real conditions, a coincidence of the results was found. The average square deviation was no more than ten percent, which once again confirmed the similarity of the two experiments. This error is due to the normalization of the spectrum, so we can say that with the actual application of the method, it may be even smaller.

Comparison of dry and wet samples showed that the spectral curves obtained when shooting the spectrum of wet samples are smoother and well distinguishable from each other (Fig. 3). Thus, some peaks recorded from dry soils are aligned during waterlogging. It was also found that in the presence of water in the sample, the so-called noise in the wavelength range from 950 nm and above decreases, i.e. the definition area increases.

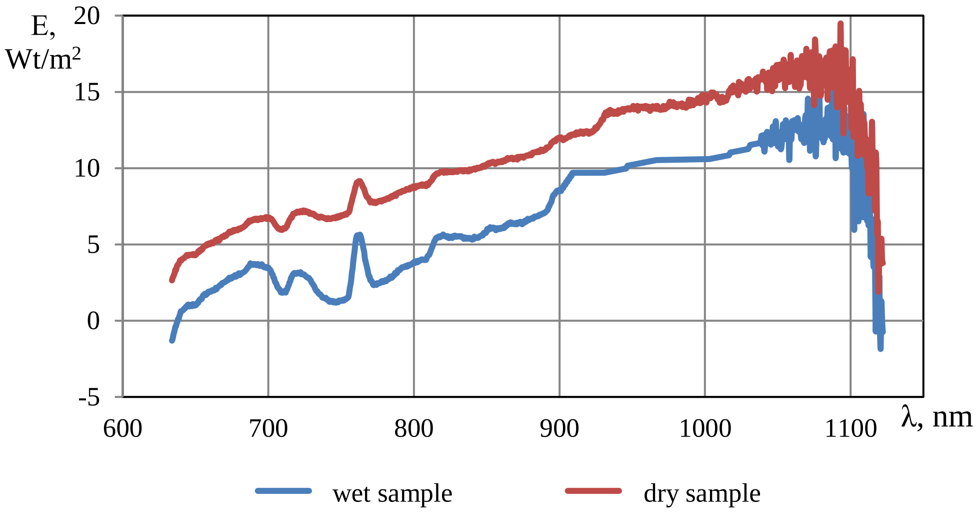

Fig. 3. Comparison of the spectra of dry and wet samples

However, there may be a discrepancy in the results of the analysis of dry and wet samples. There is a decrease in the values of the spectral characteristics of the soil when water is added to it. In addition, you can notice a change in the angle of inclination of the spectral curve.

To identify the dependence of the shape and position of the spectral line on the composition of the samples, a multidimensional calibration was performed using the multidimensional analysis software package The Unscrsmbler X. Prior to the start of calibrations, to assess the uniformity of the data structure, the modeling was initially carried out using the Principal Component Analysis (PCA) method — one of the main ways to reduce the dimensionality of the data, losing the least amount of information (noise), and to present the data in the form of projections [9]. It allows us to identify groups of samples with similar properties in a multidimensional space and determine the connectivity (correlation) of this distribution with certain properties.

It was determined that the samples from different sites have spectral differences that are not related to the indicators specified in the list of determined indicators, and form separate groups. Nevertheless, there are common features even for the sections that are scattered in the space of the main components. In particular, it is possible to conditionally identify areas with the predominant presence of samples from one of the sites, which indicates the fundamental possibility of identifying the site based on the spectral characteristics of the samples taken on it. However, this was not the purpose of this work, and no further consideration of this issue was carried out.

When comparing the formed areas and the quantitative chemical composition of the studied soils, a connection between them was found. As it can be seen in the graph of accounts, the spectral characteristics of the soils of different studied sites were divided into groups according to the content of the largest amount of a certain component (Fig. 4). In area No. 2, samples of soil cover with a higher concentration of sulfur were mainly combined, in area No. 3 — potassium and sodium, and in area No. 4 — nitrite and nitrate nitrogen. Area No. 5 is characterized by more moistened samples than others. The presence of phosphorus is recorded everywhere, but in greater quantities still in the samples that fell into area No. 1.

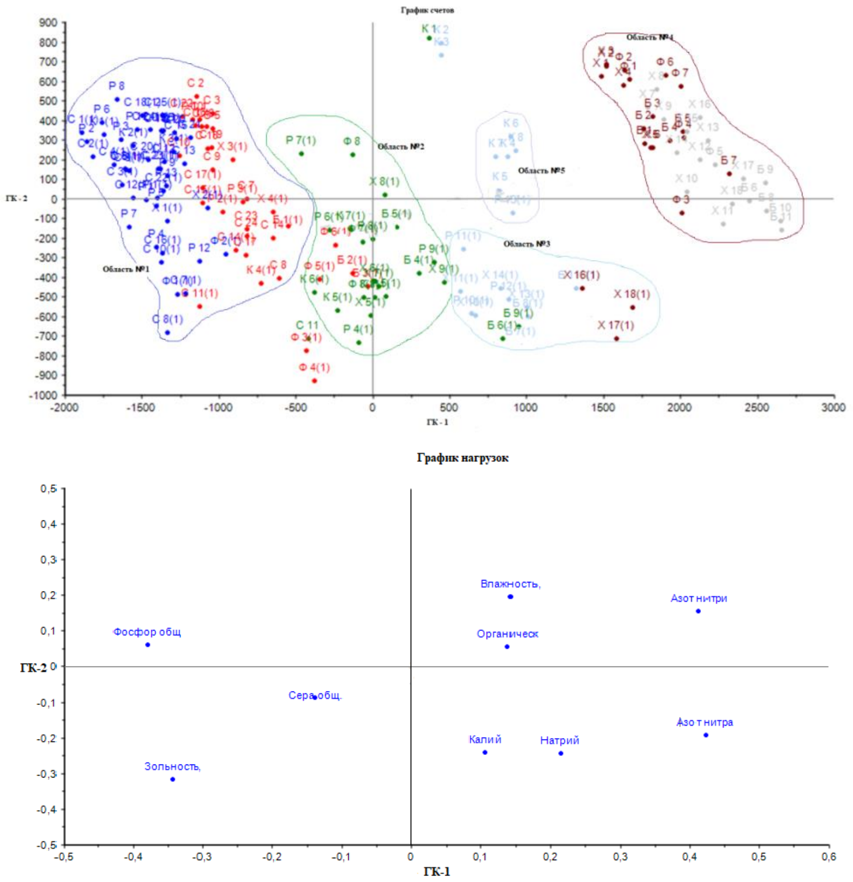

Fig. 4. Graph of samples (accounts) in a multidimensional spectral space:

ГК-1 — main component 1, ГК-2 — main component 2, С — spectral characteristics of the soils of the village of Sergievka, К — spectral characteristics of the soils of the village of Kinel-Cherkasy, Ч — spectral characteristics of the soils of the village of Bolshaya Chernigovka, Х — spectral characteristics of the soils of the village of KHvorostyanka, Р — spectral characteristics of the soils of the village of Rozhdestveno; Ф — spectral characteristics of Tolyatti soils

To identify structural features in the spectral data, a graph of variables (loads) was considered (Fig. 5). Despite the complementarity of the spectrometers in terms of the spectral range and spectral resolution of the features of the sensitive matrix, the UV and NIR-range spectra in multidimensional space are located in the form of disjoint groups of points, and modeling based on them should be carried out separately. There is a correlation of the chemical composition of soils with certain wavelengths.

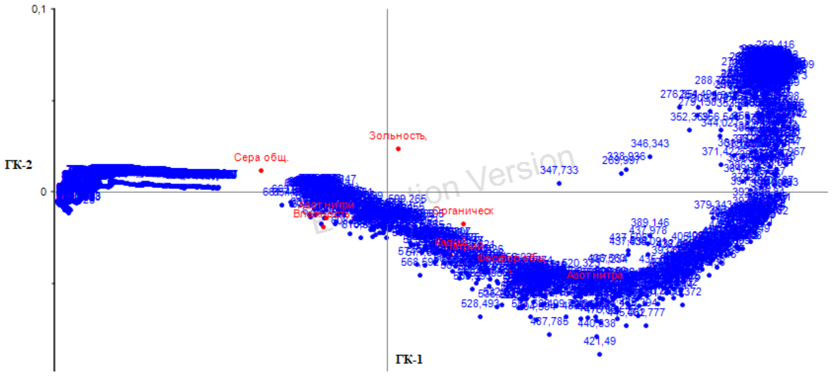

Fig. 5. Graph of loads of soil spectra of the UV range

To assess the data structure of the chemical composition and the possibility of separate determination in the array of information about the content of individual components, the modeling was also carried out in a multidimensional space using the principal component method (Fig. 6).

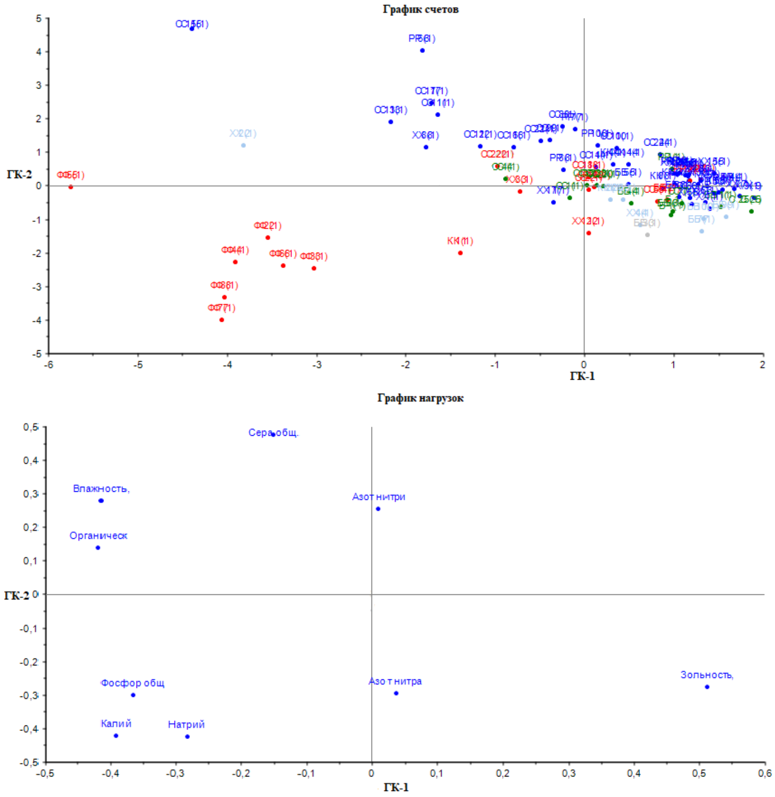

Fig. 6. Comparison of graphs of accounts and loads:

ГК-1 — main component 1, ГК-1 — the main component 2, С — spectral characteristics of the soils of the village of Sergievka, K — spectral characteristics of the soils of the village of Kinel-Cherkasy, Ч — spectral characteristics of the soils of the village of Bolshaya Chernigovka, X — spectral characteristics of the soils of S. Khvorostyanka, P — spectral characteristics of the soils of S. Rozhdestveno, Ф — spectral characteristics of Tolyatti soils

The obtained graphs allowed us to assess the situation for individual components and find a correlation between them. A correlation was found for nitrogen, phosphorus and sulfur, which can serve as a confirmation of the possibility of using spectral characteristics in assessing the quality of soil cover.

If we talk about samples from different sites, they were coordinated near the beginning of the axis of the chart of accounts, which may indicate their high dependence, i.e. similarity in the presence of a certain component, for example, nitrite nitrogen, which falls into a similar area on the load graph.

It can also be concluded that there is a negative correlation of nitrite and nitrate nitrogen in the samples. Nitrite nitrogen turns into nitrate nitrogen during the oxidation process, and this correlation is logical. The same conclusion can be drawn from the inverse correlation of such characteristics as humidity and ash content [10].

The graphs for estimating the prediction accuracy for all the chemical elements under consideration were analyzed (Fig. 7). The mean square deviation (R-Square) for phosphorus reaches 46 percent, which suggests that the model is already workable even under conditions of sufficiently high noise, fuzziness, as well as the influence of other factors and compounds. For such a non-contact method of determination, which will be used in the field, the obtained mean square deviation is acceptable for conducting a preliminary assessment of the content of a chemical element in the soil cover.

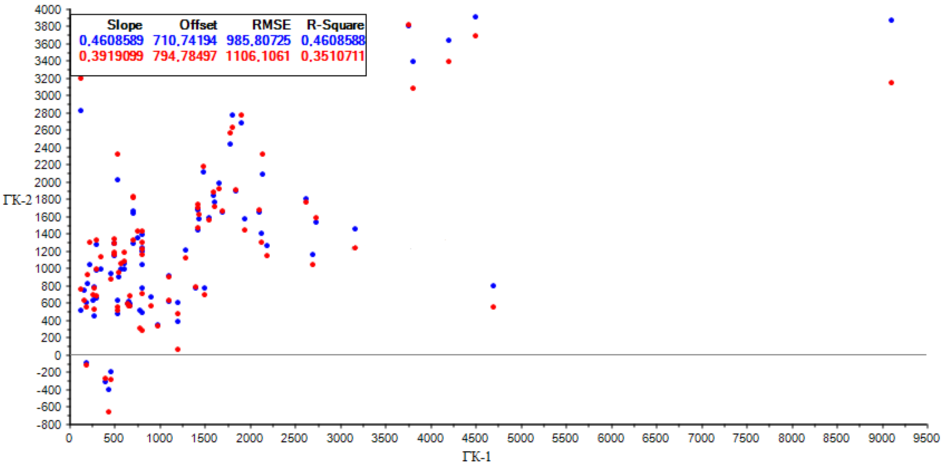

Fig. 7. Graph of estimation of prediction accuracy

In general, this model confirms the independence of the determination of soil components. The obtained result confirms the possibility of using spectral characteristics in assessing the quality of soils.

However, the use of full-spectrum models is often difficult, since it requires fast processing of significant data arrays and their long-term storage. There is a need to develop more convenient ways to work with multi-factor assessment systems for soil condition. To increase the information content, an indexing method is proposed in the format "more component content — less component content" [4].

Currently, there are about 160 variants of vegetation indices [11]. They are selected experimentally, based on the known features of the spectral reflectivity curves of vegetation and soils. The main advantage of indexes is their availability at different levels of probing with minimizing the mathematical processing of the received data. However, most of these indices are used to describe the state of vegetation cover, not soil. Thus, the use of indexing to assess the state of the soil cover is an important part of the description of the state of the objects of research and modeling.

The created calculated criteria, consisting of several intensities at certain wavelengths, may have a better correlation with the desired concentrations than directly with the spectra. They do not give absolute values, but in relative terms they can be well used in modeling the state of soils. At the same time, in the future, the use of these indices will provide an opportunity to continuously replenish and refine the model by identifying internal relationships between the indices without conducting extensive field and laboratory studies.

Conclusion. Based on the results of the work performed, the possibility of using direct spectral sensing to assess the state of soils both in direct contact and remotely was revealed. Multidimensional calibration allows us to find correlations between the forms of spectral characteristics and the chemical composition of the studied samples. The selection of the index format and the corresponding spectral bands for it is a necessary step in creating an MSS for monitoring the state of soils.

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Contribution of the authors:

T. V. Berdnikova — formulation of the purpose and objectives of the study, conducting the experiment, text preparation, formulation of the conclusions; V. V. Ermakov — scientific supervision, analysis of the research results, revision of the text, correction of the conclusions.